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THE SAN FRANCISCAN VOLCANIC FIELD ARIZONA

BY

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THE SAN FRANCISCAN VOLCANIC FIELD, ARIZONA.

By Henry Hollister Robinson.

INTRODUCTION.

LOCATION OF AREA.

The San Franciscan volcanic field, which takes its name from San Francisco Mountain, the largest volcano of the group, covers about 3,000 square miles in the north-central part of Arizona, as shown by the shaded space on the index map forming figure 1. The center of the field lies about 50 miles south of the Grand Canyon of the Colorado and the southern boundary is in part coterminous with that of the San Francisco Plateau, which forms the southwestern division of the great Colorado Plateau.

The region is easily reached, for the main line of the Atchison, Topeka & Santa Fe Railway traverses it from east to west for more than 60 miles. Flagstaff, a town of 1,500 inhabitants 10 miles south of the summit of San Francisco Mountain, is on the railroad, and a branch line runs from Williams, 34 miles farther west, to the Grand Canyon. All the more important points of interest in the field may be reached without difficulty by wagon, and outfits may be obtained at Flagstaff.

OUTLINE OF THE REPORT.

This report deals primarily with the volcanic phenomena of the region as determined in the field and laboratory. Chapter I contains a brief description of the geography of the field and Chapter II is devoted largely to the sedimentary formations and structure. The rest of the report—Chapters III to VI—treats entirely of the various features of the volcanoes and igneous rocks, both individually and collectively. Detailed descriptions of the volcanoes and lava fields are given in Chapter III; the volcanic history of the region and its correlation with the general history of the surrounding country are presented in Chapter IV. These two chapters will presumably suffice for the general reader who may desire to become acquainted with the broader volcanic features of the region. Chapter V (Petrography) is devoted entirely to the detailed description of the individual igneous rocks of the region, as represented by a selected set of type specimens. In Chapter VI (Petrology) is presented a discussion of the igneous rocks considered collectively—that is, as a series of genetically related members. These last two chapters will be more especially interesting to petrologists, although there is considerable matter in the last chapter which may also be of interest to the general reader.

EXTENT OF FIELD WORK.

The field work on which the report is based was carried on during the summers of 1901 to 1903, a portion of the time, however, being occupied by side trips to the Grand Canyon of the Colorado, the Verde Valley, and the Moqui Buttes. It was the original intention to study only San Francisco Mountain, but scattered observations made during the first summer at other localities, especially at Elden Mountain and Kendrick Peak, seemed to indicate that the region would repay wider study. The work was accordingly extended so as to embrace all the large cones that lie in the vicinity of San Francisco Mountain and some 2,000 square miles of the surrounding plateau country. The more detailed work was confined to the large cones and the laccoliths, as they presented the greatest variety of phenomena within the smallest space. Reconnaissance work was carried on in the surrounding country more especially for the purpose of determining the limits of the widespread basalt flows, their relation to the underlying sedimentary formations, and the character of those formations.

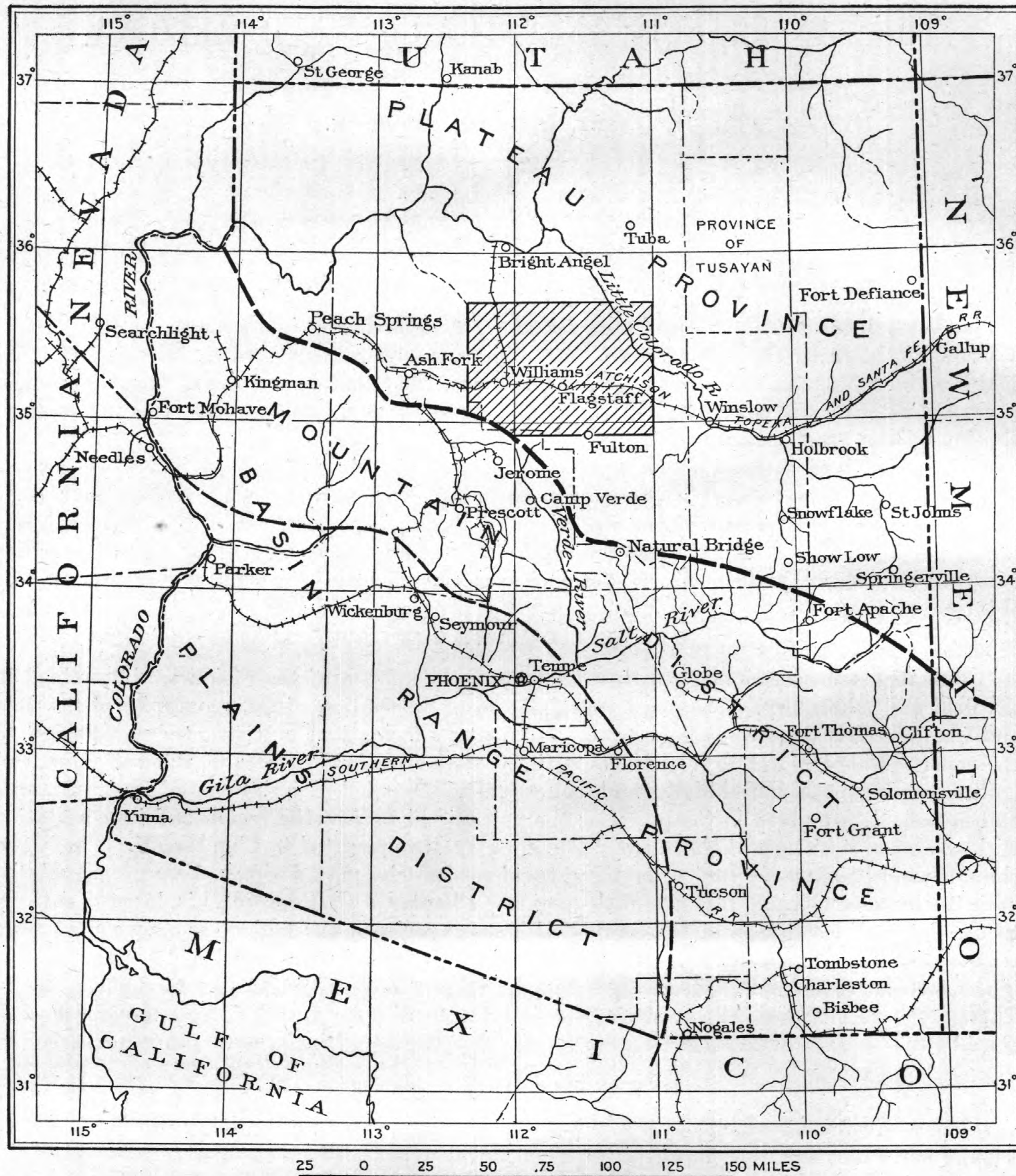

FIGURE 1.—Index map showing location of the San Franciscan volcanic field, Arizona.

PREVIOUS PRESENTATION.

In 1903 the results of the first two summers' field work were presented, under the title "Geology of San Francisco Mountain and vicinity, Arizona," as a thesis in partial fulfillment of the requirement for the doctorate degree at Yale University, New Haven, Conn. This thesis, however, forms only a minor part of the present paper, for the third season in the field and much additional laboratory work have greatly expanded the scope of the report.

ACKNOWLEDGMENTS.

The chemical analyses of the igneous rocks, with two exceptions, were made by the writer in the mineralogical laboratory of the Sheffield Scientific School, and he wishes to record his indebtedness to the late Prof. S. L. Penfield for many suggestions made throughout the course of the analytical work. The writer wishes also to express his thanks to Mr. S. H. Clapp, for the analysis of the rhyolite (No. 1) from Sugarloaf Hill and to Mr. R. J. Marsh for that of the hornblende andesite-basalt (No. 21) from Bill Williams Mountain, both of which were made in duplicate under the direction of Prof. H. W. Foote in the chemical laboratory of the Sheffield Scientific School; and to Prof. F. N. Guild, of the University of Arizona, for the analyses of the Redwall limestone, the cherty Kaibab limestone, and the residual clay resulting from the decomposition of the basalt of the first period of eruption. To Prof. L. V. Pirsson, Prof. Joseph Barrell, and Dr. H. M. Dadourian the writer is greatly indebted for advice on various parts of the work.

PREVIOUS GEOLOGIC WORK.

The first geologist to visit this region was Jules Marcou in 1853. He was followed by J. S. Newberry in 1857 and G. K. Gilbert in 1872–73. The region was not further studied until 1901, when the writer began his work. Since that time, however, several brief studies of certain features of the geology have been published, and they are referred to in later pages of this report. The early geologists accompanied expeditions whose main objects were either the location of lines of communication between the East and the Pacific coast or the acquirement of general information in regard to the country Their observations were restricted, necessarily, to the geology in the immediate vicinity of the routes of the expeditions and consequently were not always suitable or sufficiently extensive to be used as a basis for generalizations. It will be interesting, however, to review briefly the work of these geologists more especially as it relates to the volcanic phenomena of the region.

Marcou's observations[1] in the San Franciscan region were very brief, as he crossed it in midwinter, when the ground was covered with snow. His interest, however, was in the sedimentary rather than the volcanic rocks. The first three sentences quoted below are especially interesting historically and as a reminder of the controversy to which his proposal gave rise. He wrote:

> Shortly after quitting the Chiquito River we found here with the last beds of red clay of the Trias, and in concordant stratification, a magnesian or dolomitic limestone, with very regular strata from half a foot to 1 foot in thickness. Several beds contain fossils badly preserved, among which I recognized, however, a Nautilus, a Pteroceras, and a Belemnites. This formation, which is placed between the Carboniferous and Trias, corresponds without doubt to the magnesian limestone of England and is a new member which I add to the series of secondary rocks in North America. * * * From the Sierra of San Francisco to Cactus Pass the geology * * * is very complicated on account of the immense extinct volcanoes which have covered with their lavas and basaltic streams the sedimentary and granitic rocks that primitively formed this region. * * * There are four or five extinct volcanoes over this space, the largest being that of San Francisco, which is 12,000 feet above the level of the sea.

Newberry says:

> To the casual observer the San Francisco Mountain forms a most impressive feature of the scenery which surrounds it, not only from its symmetrical and striking outlines but also from its isolation. * * * Its geological structure fully accords with its physical aspects. It is volcanic throughout and is, in fact, a huge volcano whose fires have been but recently extinguished. Through one great and several minor vents, opened in the strata of the high mesa, where they have a thickness of at least 5,000 feet, a vast quantity of lava has been poured, covering with a flood of melted matter the country for many miles around and forming one principal cone with a thousand inferior ones. * * * Little disruption of the stratified rocks attended this grand exhibition of volcanic force, and the formation of the mountain seems to have been effected entirely by the ejection of matter in a state of complete fusion, through narrow orifices of unfathomable depth.[2]

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[1] Marcou, Jules, Résumé of a geological reconnaissance, etc.: Repts. Expl. and Surveys for Railroad from Mississippi River to Pacific Ocean (S. Ex. Doc. No. 78, 33d Cong., 2d sess.), vol. 3, 1856, pt. 4, p. 170.

[2] Newberry, J. S., Report upon the Colorado River of the West, War Dept., 1861, pt. 3, pp. 65–66.

The existence of great volcanoes like San Francisco Mountain and San Mateo [Mount Taylor in New Mexico] in full blast many hundred miles from the sea is a powerful argument against the theory which restricts all volcanoes to the vicinity of large bodies of water.[1]

In reading the report of the Ives expedition, of which Newberry was a member, the writer experienced some difficulty in understanding certain passages. The confusion was caused by the incorrect location of the junction of Colorado and Little Colorado rivers from 70 to 85 miles too far west. Ives and Newberry also differed as to the location of the junction, as may be seen from the following quotations and figure 2. This probably accounts for the indefinite indication of their map of the course of Colorado River north of its supposed junction with the Little Colorado. Ives[2] says:

A trail was encountered * * * [which] headed directly for the north side mountains [Mount Trumbull]—the peaks already spoken of as seen on the *opposite* [*north*] *bank of the Colorado*. * * * A good view was obtained of the walls of the Flax [Little Colorado] River canyon and its mouth approximately located. The junction was below the mouth of Cascade [Cataract] Creek, showing that that stream is not * * * a tributary of the Colorado.

Newberry's account,[3] written from the same locality as that of Ives, says:

The angle of the mesa included between the Great and Little Colorados, *on the north side of the latter stream*, * * * overlooks the valley in a nearly perpendicular wall [Mount Trumbull] some 4,000 feet in height. * * * In the northwest the high mesa at *the junction of the two Colorados* formed a most conspicuous object.

Ives thus made the junction east of Mount Trumbull, whereas Newberry placed it on the west side. As the result of supposing the junction at this locality, Newberry describes the

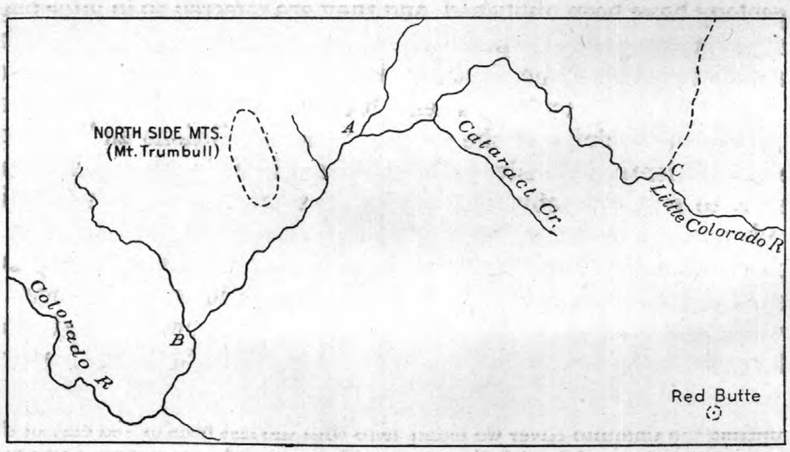

FIGURE 2.—Map showing junction of Colorado and Little Colorado rivers as located by Ives and Newberry. *A*, Location by Ives; *B*, location by Newberry; *C*, correct location.

region between the present Aubrey Cliffs and Coconino Plateau as the valley of the Little Colorado, whereas it is actually that of Cataract Creek.

The work of G. K. Gilbert,[4] although a reconnaissance, was more extended than that of Marcou and Newberry. He noted, in adition to the rocks mentioned in the quotation below, the presence of a small amount of rhyolite in San Francisco Mountain. He determined that—

The San Francisco group includes a series of large cones of trachyte, the product of massive eruptions, and a great number of small basaltic cones, associated with broad and in part thick sheets of basaltic lava. The trachyte has perhaps the greater mass, but the basalt covers by far the greater area. The large cones, though they may be justly called a group, are separated by intervals of several miles.

It is well worthy of note that the majority of these eruptions among the plateaus rest upon nearly level strata, * * * where the structure is so simple * * * [that] a local structure imposed by the extrusion of lava could not escape detection, and we have direct evidence in its absence that the erupted rocks, in passing through, have not uplifted the sedimentary. This remark applies not merely to the eruptions of basalt, which we know * * * to have been a tolerably thin fluid, but also to the most viscous trachyte, which, in the case of San Francisco Mountain, for example, has been built, not a scoriaceous mass, but a pyramid of compact lava, to a height of nearly 5,000 feet, with slopes of 10° to 20°.

[1] Newberry, J. S., Report of exploring expedition from Santa Fe, N. Mex., to junction of the Grand and Green rivers of the Great Colorado of the West, in 1859, War Dept., 1876, p. 62.
[2] Ives, J. C., Report upon the Colorado River of the West, War Dept., 1861, pt. 1, p. 110.
[3] Op. cit., pt. 3, p. 61.
[4] U. S. Geog. Surveys W. 100th Mer., vol. 3, pt. 1, 1875, Geology, pp. 129-131.

CHAPTER I.

GEOGRAPHY.

PHYSIOGRAPHIC DIVISIONS OF ARIZONA.

The physiographic divisions of Arizona were first broadly outlined by Gilbert,[1] who recognized the Plateau and Basin Range provinces. Later Glassford[2] further divided the Basin Range province into the Plain and the pro-Plateau. A similar threefold division, under the headings Plateau, Mountain, and Desert districts, was adopted by Ransome[3] in his reports on the Globe and Bisbee copper districts. The same divisions are recognized in this report under a slightly different and more uniform nomenclature. The region is thus divided into the Plateau and Basin Range provinces, and the Basin Range province is subdivided into the Mountain and Plains districts. (See fig. 1, p. 10.)

The Plateau and Basin Range provinces are, on the whole, topographically distinct from each other. The former is a broad expanse of nearly horizontal strata disturbed in only a few places; the latter is a region of faulted and tilted block mountains separated by flat-floored valleys. The difference between the Mountain and Plains districts is of another order. Throughout both districts there are short isolated mountain ranges from 1,000 to 4,000 feet high, with parallel trend. The intervening rock-floored or waste-filled valleys are essentially flat. The distinction here is in the comparative abundance of similar topographic forms. In the Mountain district the areas occupied by the ranges and valleys are about equal in extent; in the Plains district the area covered by the valleys largely predominates over that covered by the ranges.

The Plateau province occupies the northeastern portion of Arizona, comprising an area of about 45,000 square miles, or 40 per cent of the State. To the north and east it extends into the adjacent States. From the Colorado to the headwaters of Salt River it terminates, for the most part sharply, in the Grand Wash and Aubrey cliffs, which rise to heights of 1,000 to 2,000 feet and expose in their faces the horizontal strata of the Plateau. The general elevation of the region is 6,500 feet and is much greater than that of the Basin Range province. The summits of several of the volcanoes upon its surface have elevations of over 10,000 feet; only along Colorado River and its tributaries does the elevation of the Plateau fall below 5,000 feet. The essential horizontality of the strata in the Plateau province, from which there are but slight departures except where there has been monoclinal folding, is in marked contrast with the structure in the Basin Range province. The fact that the strata are practically level has probably given rise to the idea that the surface is smooth, as is implied in the expression "level mesa," not infrequently applied to it. The contrary is perhaps nearer the truth, for erosion has cut many profound canyons, including the Grand Canyon of the Colorado, which attains a depth of over 5,000 feet. Volcanic forces have been active at numerous localities and the erupted lavas have built up many large and small cones and spread out over thousands of square miles. Two opposing forces, therefore, have produced the detailed topography of the Plateau—erosion, which is destructive, and volcanism, which is constructive.

The Basin Range province comprises the entire southwestern part of the State and is larger than the Plateau province, for it covers 68,000 square miles. It is divided into the Mountain and Plains districts.

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[1] Gilbert, G. K., U. S. Geog. Surveys W. 100th Mer., vol. 3, 1875, chap. 1.

[2] Glassford, Lieut. W. A., Report on the climate of Arizona; Ex. Doc. 287, 51st Cong., 2d sess.

[3] Ransome, F. L., Geology of the Globe copper district, Arizona: Prof. Paper U. S. Geol. Survey No. 12, 1903; Globe folio (No. 111), Geol. Atlas U. S., U. S. Geol. Survey, 1904; Geology and ore deposits of the Bisbee quadrangle: Prof. Paper U. S. Geol. Survey No. 21, 1904; Bisbee folio (No. 112), Geol. Atlas U. S., U. S. Geol. Survey, 1904.

The Mountain district lies between the Plateau province and the Plains district and is the smallest of the three physiographic divisions, covering 27,000 square miles, or 24 per cent of the region. It extends southeastward from the Colorado to Salt River as a belt of country about 50 miles wide. At Salt River it widens out, the western boundary running southward into Mexico. Farther east the district coalesces with a similar one in New Mexico and extends a short distance beyond the Rio Grande. In this district there are some thirty mountain ranges of the basin-range type, which occupy, as estimated from the Geological Survey's large-scale topographic map of the United States, 15,000 square miles, or 55 per cent of the area, thus leaving 45 per cent for the valleys. The average area covered by a range is 500 square miles and the ratio of its width to its length is 1:2.8. The entire region stands at a higher general elevation above sea level than the Plains district, but lower than the Plateau. The mountains range in height from about 4,000 to 6,000 feet and rise 2,000 to 4,000 feet above the valley bottoms. The summits of the Bradshaw and Pinal mountains, however, are nearly 8,000 feet above the sea. Throughout the district the ranges exhibit a marked parallelism in trend, which in general is northwest. At the Mexican boundary, however, the trend is nearer north-northwest, and at Colorado River it swings around to north, a direction in which it continues through Nevada.

An estimate of the relative areas of range and valley in the Basin Range country was made from the map which accompanies Spurr's paper on the geology of Nevada south of the fortieth parallel.[1] Exactly the same values were obtained as for the Mountain district of Arizona, and although this should be considered a coincidence, it illustrates the intimate relation of the two regions. In Nevada, however, there are sixty ranges covering 12,000 square miles, against thirty covering 15,000 square miles in the Mountain district of Arizona. The area covered by the average range in Nevada is thus much smaller and the ratio of the width to the length of the ranges is also less, being 1:2.

The mountains and valleys in the Basin Range country are so sharply defined that it is possible to formulate a quantitative definition of the topography of the region, namely, that *typical basin-range topography is represented by a region where the area occupied by the mountain ranges due to block faulting is equal to that occupied by the valleys.* It will be understood that this definition applies primarily to the ranges of the Great Basin, an arid region with interior drainage, and to the ranges in their present stage of development. With only slight modification the definition may be extended to cover the ranges in Arizona, an arid region with exterior drainage. Definitions of this character seem preferable to qualitative definitions, but various difficulties would have to be overcome in formulating them for the more complex physiographic types. The science of physiography is probably not in the stage of development where too great a refinement of definition should be attempted, although the quantitative idea might be beneficially used in the description of the more simple and clearly marked types, of which basin-range topography is an example.

The Plains district comprises the remaining 41,000 square miles, or 36 per cent, of Arizona. It is distinguished from the Mountain district by the presence of wide and long level valleys separated by rugged isolated mountain ridges 1,000 to 2,000 feet in height. The valley area clearly predominates over that covered by the ridges. An estimate based on the large-scale map of the United States shows that the valleys occupy 85 per cent of the area, thus leaving 15 per cent for the ridges. This is practically the same as McGee's estimate[2] that one-fifth (20 per cent) of the Sonoran district of Mexico, which lies immediately to the south, consists of mountains. The valleys have been described by Antisell[3] as follows:

> Standing at the foot of these [Bighorn or Goat] mountains and looking backward over the trail traveled, the character of the country becomes apparent; it is an immense extended plain as far as the eye can reach (about 60 miles), sloping slightly to the southwest, and equally level north for 35 miles, the horizontality only disturbed by the isolated hills or ranges described, whose general direction is N. 60° W. The soil of the plain is uniform—a feldspathic or

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[1] Spurr, J. E., Descriptive geology of Nevada south of the fortieth parallel and adjacent portions of California: Bull. U. S. Geol. Survey No. 208, 1903.

[2] McGee, W J, Sheetflood erosion: Bull. Geol. Soc. America, vol. 8, 1897, p. 89.

[3] Antisell, Thomas, Repts. Expl. and Surveys for Railroad from Mississippi River to the Pacific Ocean, vol. 7, pt. 2, 1856, p. 133.

granitic sand, with occasional drifts of fine quartz sand, easily impressed by the hoof of the beast, and brilliant, so as to pain the eye in midday by the reflection of the sunlight.

There are between 50 and 60 mountain ridges in the district, so that the area covered by the average ridge is about 100 square miles. Fully half of them, however, occupy an area averaging less than 50 square miles to a ridge. Their ratio of width to length is 1 : 4.5. Like the ranges to the northeast, the ridges show a general parallelism in trend, which is in a northwesterly direction. They are much more scattered and more highly dissected than the ranges in the Mountain district and have aptly been called "buried mountains."

GEOGRAPHY OF THE VOLCANIC FIELD.

TOPOGRAPHY.

In the more distant views of the volcanic field one is impressed only by the large cones and their complete isolation from one another. From all points of view San Francisco Mountain stands out with great distinctness, rising with graceful outline to a height of 12,700 feet above the sea, or over 5,000 feet above the surrounding country. Kendrick Peak, 11 miles to the northwest, is second in size and has an elevation of 10,500 feet above sea level, or 3,500 feet above its base. Bill Williams Mountain and Sitgreaves Peak, in the western part of the region, rise not more than 9,500 feet above the sea, or 2,500 feet above the adjacent country. O'Leary Peak and Elden Mountain, situated closer to San Francisco Mountain on the east and southeast, have elevations of about 9,000 feet and rise 2,000 feet above their bases. Mormon Mountain occupies a somewhat isolated position 28 miles south of San Francisco Mountain. It is the smallest of the large volcanoes, for its elevation is 8,600 feet above sea level, or 1,500 feet above the surrounding region. Small volcanic cones are scattered about with great irregularity; at some localities they are grouped closely together, at others they are entirely asbent. To a person riding among them they appear to be rather insignificant features of the landscape as compared with the large cones, for few of them attain heights of more than 700 feet. It is only when they are viewed from the commanding summits of the higher peaks that they are seen to produce considerable detail in the topography. Although the surface slopes throughout most of the field are gentle, they bring about notable changes in elevation over long stretches. This may be best appreciated from the general geologic map (Pl. III, p. 20) which has a contour interval of 1,000 feet.

The surface of the country south of the railroad, from the vicinity of Flagstaff to the western boundary of the field, is fairly level and stands at an elevation of 6,500 to 7,000 feet. The field is abruptly terminated on the west and south by the precipitous Aubrey Cliffs, which gradually increase in height from 500 feet near Williams to more than 1,000 feet at Oak Creek. Bill Williams Mountain is the only large volcano in this part of the region and small cones are less numerous than in any other locality except the extreme eastern part. Several canyons have been cut back from the Aubrey Cliffs into the plateau. Those of Sycamore and Oak creeks on the south are the largest. They are 1,000 and 1,500 feet deep, respectively, and about 8 miles long.

The greater part of the region north of the railroad and west of San Francisco Mountain has much the same general elevation as that to the south, although it is somewhat higher in the vicinity of the large cones. Northwest of a line joining Bill Williams Mountain and Red Mountain, at the head of Hull Wash, the surface slopes gently down to 6,000 feet at the head canyons of Cataract Creek. Kendrick and Sitgreaves peaks, as well as many small cones, are situated in this part of the field. They introduce into the landscape a noticeable diversity of relief, which is reflected in a broader and more subdued form in the many lava flows.

The country immediately north of San Francisco Mountain and as far west as Kendrick Peak has an elevation of about 8,000 feet. The general surface does not maintain this elevation, however, but slopes down gradually to the north at an angle of 1½°, until at the edge of the mesa overlooking Hull Wash, it has an altitude of 6,700 feet. A number of basalt cones are situated in the neighborhood of the large volcanoes, but farther north they are absent and the surface has only the minor relief produced by lava flows.

East of San Francisco Mountain is a thickly clustered group of small cones known as the Black Hills, and in the northeastern part of the field is another group, perhaps equal in number but more widely scattered. In general appearance, however, the country is much the same as elsewhere in the field and may be described as consisting of a gently rolling surface whose continuity is broken by numerous conical and dome-shaped hills, few of which exceed 1,000 feet in height, and here and there by a cone of large size. (See Pl. I, *A*.) The entire eastern part of the field differs considerably in elevation from that to the west. Although having an altitude of 7,000 feet in the vicinity of San Francisco Mountain, it drops off with marked uniformity and at Little Colorado River, distant 20 miles, it stands at 4,500 feet.

The southeastern part of the area described in this report, in contrast to the rest of the field, presents an unbroken expanse of sedimentary strata. The surface is wholly lacking in relief, though cut by many washes and canyons, of which Canyon Diablo is the largest. It slopes gently northeastward from an elevation of 7,000 feet on the east side of Black Mesa to 5,000 feet at Little Colorado River.

DRAINAGE.

GENERAL CHARACTERISTICS.

The San Franciscan volcanic field may be divided into three large drainage areas, but all the surface water eventually finds its way into Colorado River. The eastern half of the area is drained by the Little Colorado, and the northwestern one-eighth drains into Cataract Creek, both of which streams join the Colorado in the Grand Canyon. The southwestern three-eighths drains into Verde River and, through the Gila, finally into the Colorado at Yuma, 60 miles from its mouth.

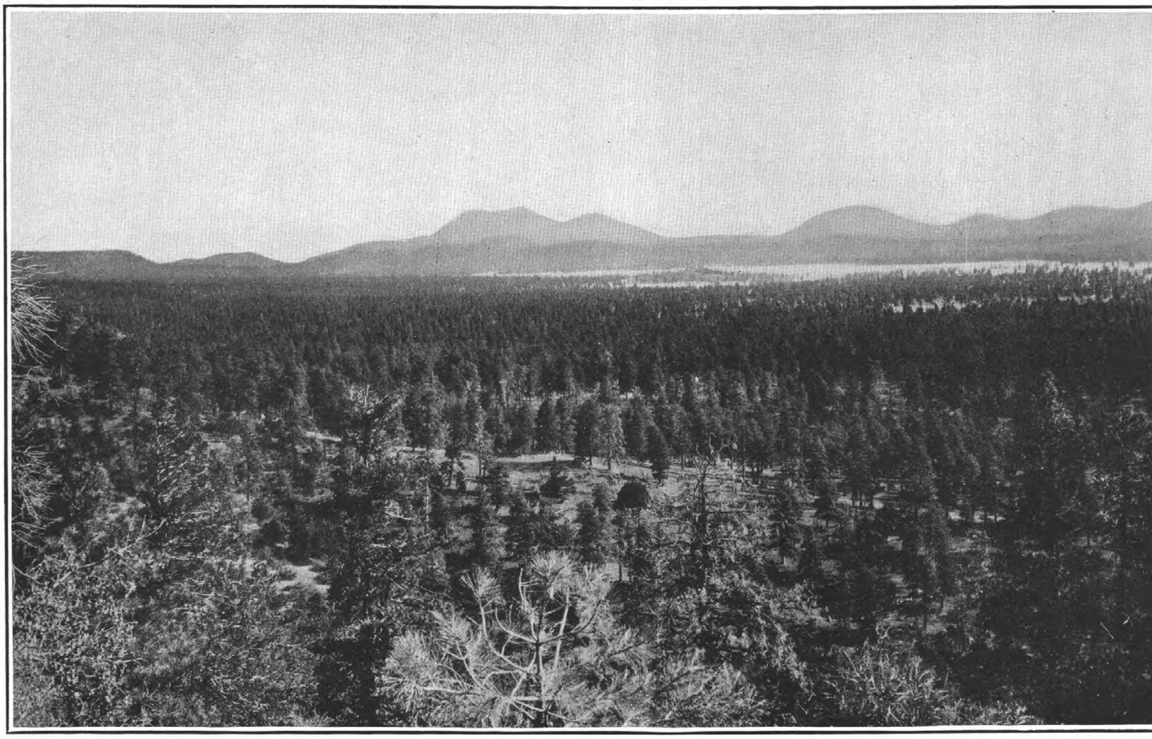
The drainage system of the region is very simple and consists of about 12 principal water courses or washes radiating from the higher parts of the field. Within the lava field the courses of these washes are not everywhere well marked and have frequently been modified by successive lava flows, but in the sedimentary rocks they are well defined locally as shallow valleys, more generally as precipitous walled canyons.

The common characteristic of all these washes and canyons is their dryness. After a heavy shower or cloudburst the wash draining the area on which the rain has fallen carries water for a short time and then resumes its accustomed dryness. Oak Creek is the only perennial stream within the borders of the lava field. It is fed by several large springs that break out at the intersection of two fault planes at the head of the canyon 500 feet below the surface of the surrounding country.

The absence of perennial streams is a serious obstacle to travel and makes it necessary to depend for water on springs, lakes, and water pockets, or "tanks," as they are called in the Southwest. Springs furnish the most reliable supply and the larger ones may be considered permanent, as they have not failed since the region was opened, over 30 years ago. The smaller springs, as well as the lakes and tanks, are transient; their existence depends on a very rainy season or series of seasons.

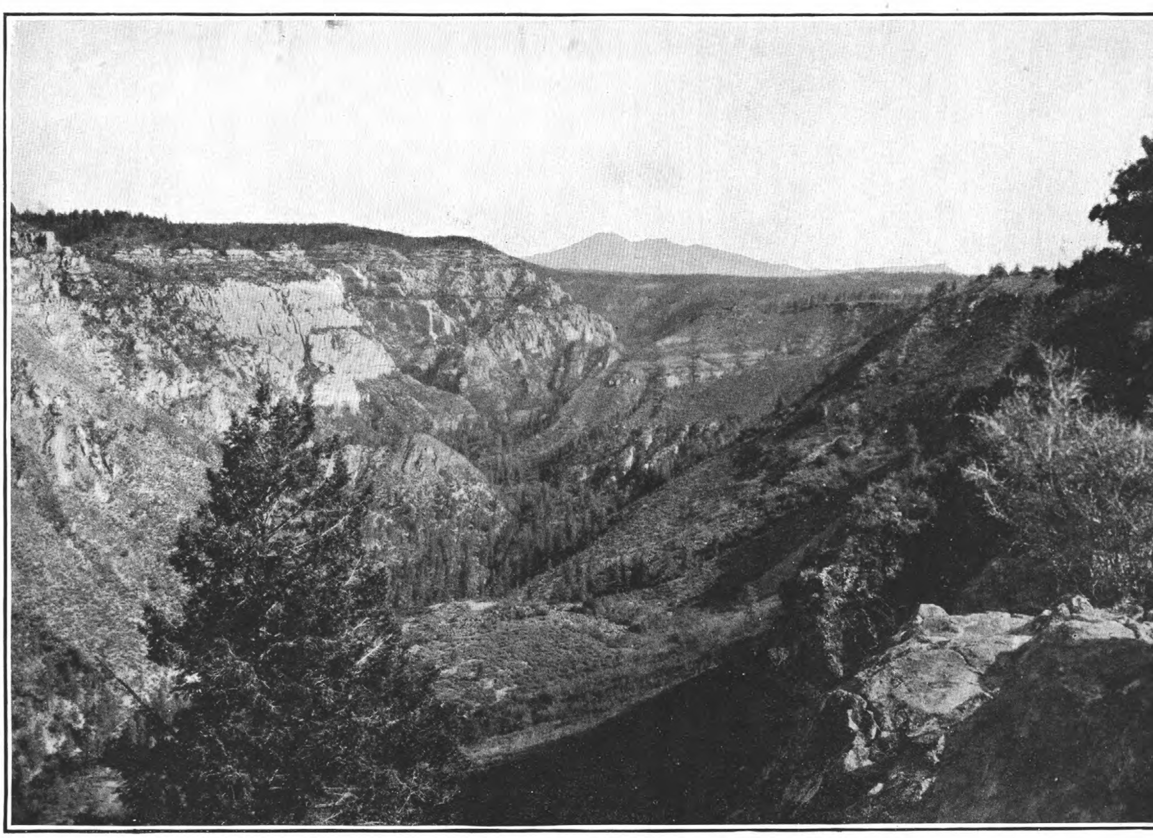
Little is known concerning the underground drainage of the region, although the great extent of the limestone formations and the presence at many points of "bottomless" pits and fissures indicate that it may be of some importance. Gilbert[1] has described such a fissure at the McMillan ranch, near Canyon Diablo, in the Little Colorado Valley. This fissure contains running water at a depth of 100 feet and is supposed to be due to tension in the brittle limestone, as there are several small faults of 10 to 50 feet throw in the region. A similar fissure may be seen on the Tuba road, some 12 miles west of the Little Colorado. Several pits due to the solution of the limestone by percolating surface waters were observed, such as the Bottomless Pit (Pl. II, *B*), on the road to the cave dwellings in Walnut Canyon. This pit is situated in a small silt-filled valley and has been but recently opened. The underground drainage is not yet well established, for the amount of water brought to it in the spring is some-

[1] Gilbert, G. K., A rock fissure: Science, vol. 2, 1895, p. 117.



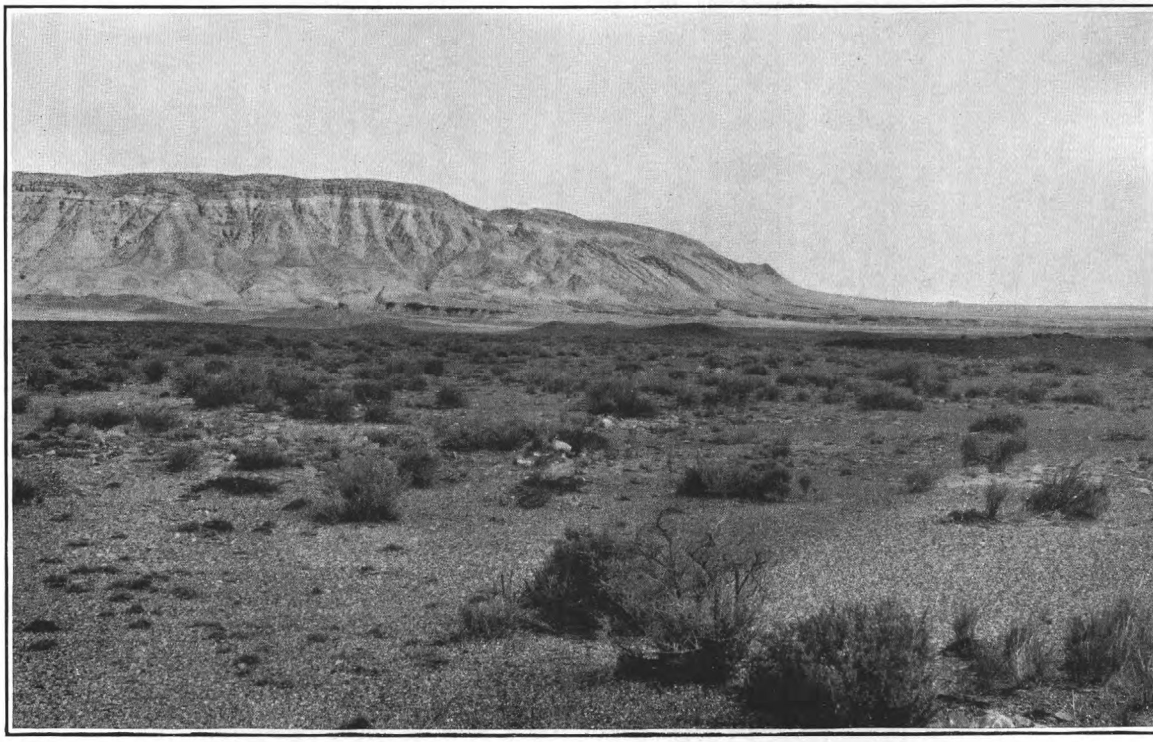
A. BLACK BILL PARK, EAST OF SAN FRANCISCO AND ELDEN MOUNTAINS.

Showing parklike character of the country in the pine zone at 7,000 feet and scattered cones. The double cone in center is O'Leary Peak. Sunset Peak is next on the right.

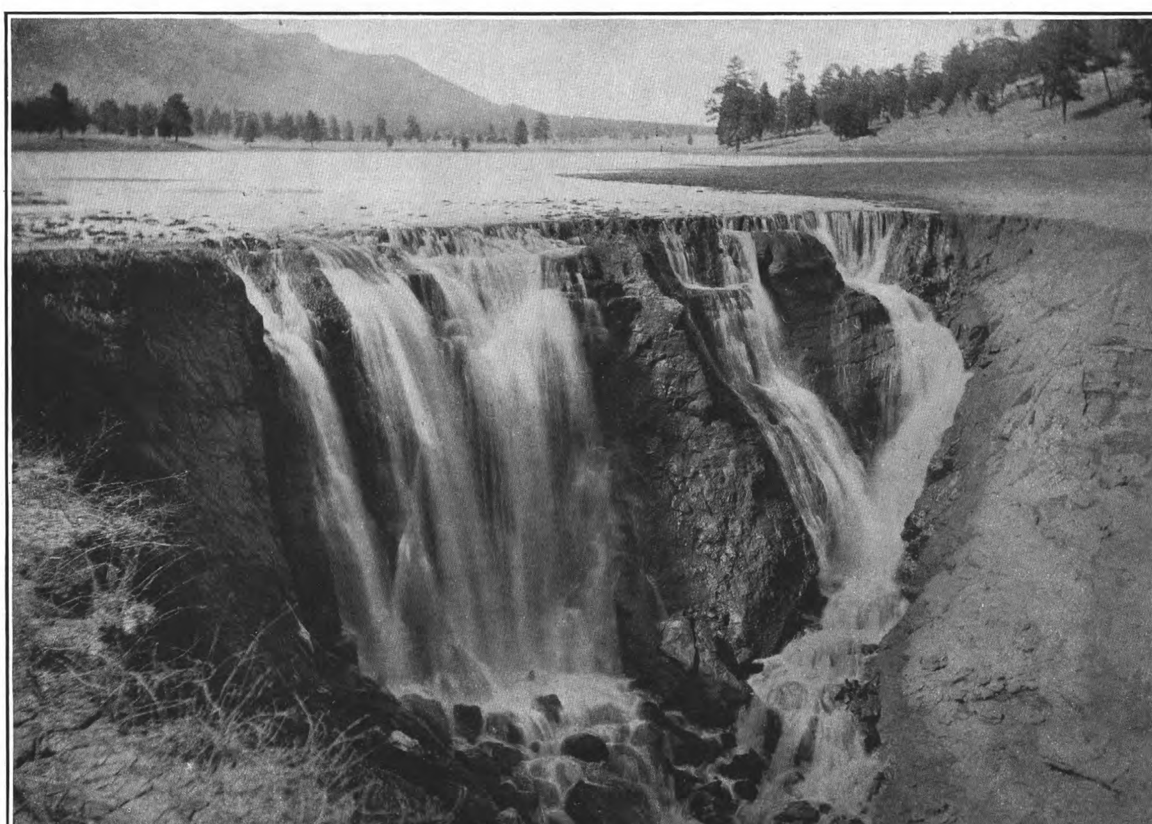


B. OAK CREEK CANYON.

Looking north from point near head. Presence of a fault, which has controlled the course of the stream, is indicated by the discordance in the elevations of the opposite walls of the canyon.



A. COCONINO MONOCLINE AT COCONINO POINT, LITTLE COLORADO VALLEY.
Looking north.



B. BOTTOMLESS PIT, SOUTH OF ELDEN MOUNTAIN.
Showing development of underground drainage. Photograph by A. E. Hackett, Flagstaff, Ariz.

times too great to be carried off and a temporary lake is then formed, such as commonly existed before the pit was developed. A similar depression is reported to exist at the south end of the Bellemont Prairie, and the deep, steep-sided lake sites of the Black Mesa, such as Stonemans Lake, have presumably resulted from the solution of the underlying limestone.

SPECIAL CHARACTERISTICS.

Lava flows have naturally caused numerous minor changes in the drainage system of the region. The damming of watercourses by flows has given rise to many small lakes. Some of these still persist; others have been drained by the cutting down of the obstruction that formed them, although not before they had been more or less filled with sediment. The grass-covered glades, which are picturesque features of the landscape throughout the pine forest, generally indicate the location of former lake sites. Many of the open spaces, especially the larger ones, are not, however, of this nature. Two typical examples of drainage modification by lava flows may be seen on Little Colorado River at Black Falls and Grand Falls.

The Little Colorado for several miles above and below Black Falls occupies a shallow valley into which a small isolated lava stream was poured, covering an area of about 3 square miles and having a thickness of possibly 25 feet or more. This flow ponded back the river for a distance of 2 miles, forming a shallow lake, and made it seek a new course, nearly in line with its former channel, partly across and partly along the side of the lava flow. Since the obstruction occurred the river has cut a channel in the lava 100 feet wide and 10 feet deep for 200 feet above the downstream end of the flow. At the head of this channel the river cascades over the bare lava for a short distance with a drop of less than 10 feet, but above the so-called falls it flows on the surface of the lava at practically the same grade it had before the damming took place. As may be seen, the changes at this locality have been very slight.

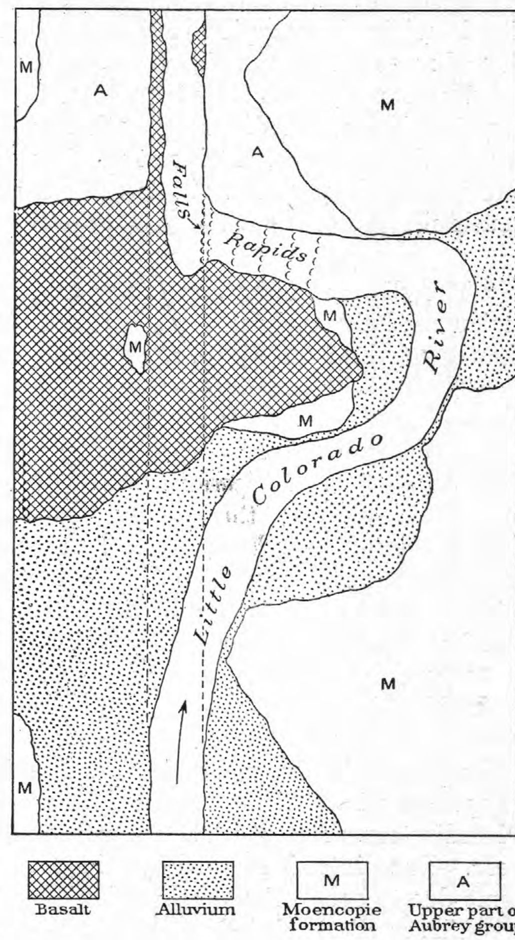


FIGURE 3.—Sketch map of Grand Falls, Little Colorado River.

The phenomenon at Grand Falls is on a much larger scale and possesses greater interest. (See fig. 3.) Here the river formerly flowed in a perpendicular-walled canyon, 125 feet deep, cut in limestone. A lava stream, following the course of a side wash, reached the river, completely filled the canyon, and spread over the country east of the river for a quarter of a mile. The lava also ran down the canyon for 1½ miles, filling it from side to side in a wedge-shaped mass. It must also have filled the canyon in the same manner above the point of inflow, though this part is not now exposed.

A narrow lake was formed on the upstream side of the lava flow, in which sediments were deposited and all traces of the former canyon hidden. Occasionally, however, when the river is in flood and strongly scouring, the west edge of the canyon is exposed for short distances. This lake must have been very transient, for the cutting down of its outlet in the soft red shale and sandstone that overlie the limestone could not have taken more than a comparatively few years. The river established a new channel around the east end of the lava flow and fell into the old canyon at a right angle to its former course and just below the main point of obstruction. At first the fall was but a few feet, the distance from the rim of the canyon to the surface of the lava filling. But as the lava was eroded the height increased, until now, the lava at this point having been entirely removed, the fall is equal to the original depth of the canyon—125 feet. The width of the falls is about 400 feet and appears to have been constant throughout the process of development.

The river has made some headway in removing the thin-bedded limestone strata that form the upper part of the canyon wall, and it cascades over their eroded edges for a quarter of a mile at a grade of 2°. It then falls abruptly over the edge of a thick bed of limestone and after flowing on the surface of the underlying stratum for 50 feet again drops vertically to the bottom of the canyon. The lowest bed of limestone has not retreated more than 20 feet from the position it originally occupied in the canyon wall. Below the falls about one-half of the wedge-shaped mass of lava remains along the west side of the canyon.

The exposures at Grand Falls are so complete that the amount of material eroded can be very closely calculated. On the other hand, the flow of the river and the rate at which it erodes are wholly unknown. It is not possible, therefore, to determine the age of the falls, however interesting the problem. It is sufficient to say that they are, in geologic terms, distinctly youthful.

CLIMATE.

The climate of the San Franciscan volcanic field is typically that of an arid to semiarid region predominantly under solar control, as the cyclonic element does not constitute more than one-fifth of the whole.

The highest temperatures are experienced in the Little Colorado Valley, where the elevations are lowest. The mean annual temperature there is about 56°, the average absolute maximum is 100–105°, and the minimum is zero. In the central and western parts of the field, at elevations of about 7,000 feet, the mean annual temperature is approximately 46°, the average maximum is 92°, and the minimum is −13°. Throughout the region insolation is very great and produces a wide range in temperature from day to night. At Flagstaff (elevation 6,900 feet) this range averages 30° for the year, with an average maximum of 36° in June and a minimum of 25° in February and March. In the Little Colorado Valley, owing to the decreased cloud cover and the absence of vegetation, the daily range is somewhat greater.

There are two wet seasons—one in summer, the other in winter—which are separated by much drier periods. The summer season is characterized by local showers due to convectional atmospheric currents. In the higher parts of the region many of these storms are severe and a few reach the proportions of cloudbursts. In the Little Colorado Valley, however, the temperature is so high that the lighter showers are evaporated before they reach the ground. Thunderstorms are especially frequent in summer, but have been reported in every month of the year. The winter is marked by rainstorms and in the higher parts of the field by snowstorms—some due to convectional atmospheric currents, some to cyclonic disturbances.

The smallest rainfall in the region—less than 5 inches a year—occurs in the Little Colorado Valley. At Williams, in the southwestern part of the field, the rainfall amounts to 15 inches, and at Flagstaff it is 22 inches. The rainfall at Flagstaff is greater than at any other station in Arizona and is influenced, no doubt, by the proximity of San Francisco Mountain. The average snowfall at Flagstaff is 85 inches a year and is distributed through all the months except June to September. About 70 per cent of the total falls in January, February, and March. The largest snowfall is, of course, on San Francisco Mountain, and not uncommonly a small snow field persists through the summer in the ravine in which Snowslide Spring is located, immediately south of the core ridge. The chief characteristic of the rainfall is its extreme variability. The difference in the mean annual rainfall at Flagstaff is over 100 per cent; in the Little Colorado Valley it may amount to 1,000 per cent—that is to say, in some years practically no rain falls in that area. The differences in the monthly precipitation from year to year are even more striking. At Flagstaff the wettest month of the year—February, with an average rainfall of 2.65 inches—shows a maximum of 8.36 inches and a minimum of 0.28 inch.

FORESTS.

The wide range in elevation in the San Franciscan volcanic field and the accompanying climatic variations bring about striking changes from place to place in the character of the vegetation. Although the field is encircled on all sides by a barren and arid region, much of which is in fact a desert, the higher parts of the field are clothed in a beautiful forest of juniper, pine, and spruce. The abrupt change from desert to forest, so clearly seen in passing from the valley of the Little Colorado westward, delighted the early explorers as it delights the traveler of to-day. Beale,[1] who traversed the region in 1858, remarked that "No one could pass through this country without being struck by its picturesque and beautiful scenery, its rich soil, and its noble forests of timber. The view from our camp of this morning is unsurpassed in the world."

A study of the plant life of this general region by C. Hart Merriam[2] led him to divide it into seven distinctly marked zones, ranging from subtropical in the Little Colorado Valley to Alpine at the summit of San Francisco Mountain. Of these zones, the one known as the pine zone and marked by the presence of the yellow pine (*Pinus ponderosa*) is the most important commercially as well as the most beautiful. These pines, which average over 100 feet in height, grow between elevations of 7,000 and 8,200 feet and form a magnificent open forest. Throughout its extent there is practically no underbrush; in summer the ground is covered with an abundant growth of grass, and the forest gives one the impression of an immense cultivated park.

[1] Beale, E. E., Report on wagon road from Fort Smith, Ark., to the Colorado River: H. Ex. Doc. No. 42, 36th Cong., 1st sess., 1860.

[2] Merriam, C. H., Results of a biological survey of the San Francisco Mountain region and the desert of the Little Colorado River, Ariz.: North American Fauna No. 3, U. S. Dept. Agr., 1890.

CHAPTER II.

REGIONAL GEOLOGY.

TOPICS COVERED.

This chapter is devoted to the nonvolcanic geologic features of the region—the sedimentary rocks, the structure, and the glaciation and alluviation of San Francisco Mountain. The greater part of the chapter is devoted to the description of the sedimentary formations and the discussion of their origin and correlation with the corresponding formations of the surrounding country. The sedimentary record is so entirely unrelated to the volcanic record that it is advisable to treat the two separately. The youngest sedimentary rocks, except the Quaternary alluvial deposits, are of Triassic age, whereas the first lavas were not erupted until Pliocene time. The history of the region during this hiatus from the Triassic to the Pliocene will be omitted, as observations in the surrounding country are too incomplete to permit a satisfactory outline of it to be given. A general geologic map of the region forms Plate III.

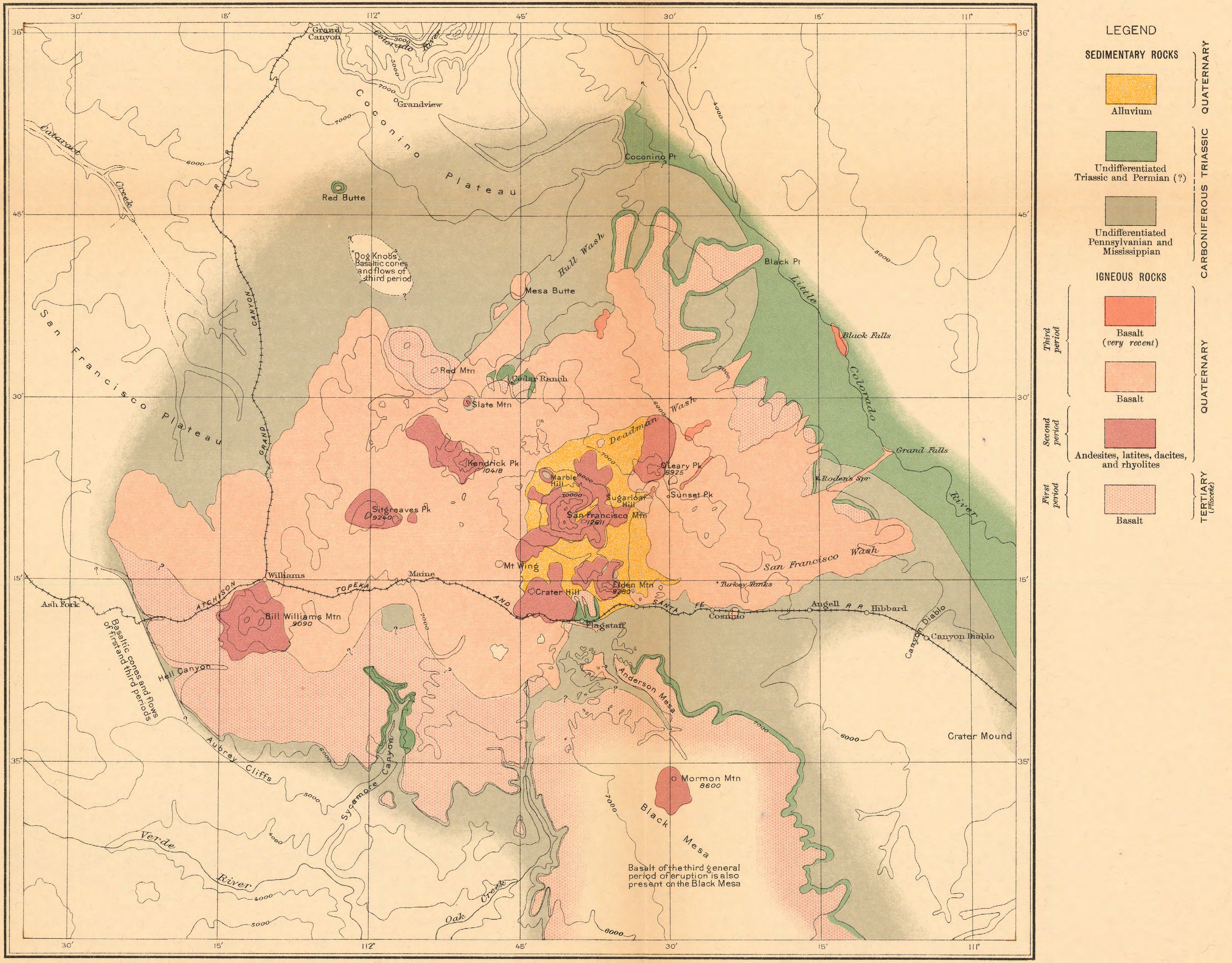
OUTLINE OF GEOLOGIC HISTORY BASED ON THE SEDIMENTARY FORMATIONS.

The oldest rocks of the region are the pure limestones of the Redwall formation, of Mississippian (lower Carboniferous) and Pennsylvanian (upper Carboniferous) age. The red sandstone of the Supai ("Lower Aubrey") formation, the cross-bedded Coconino ("Upper Aubrey") sandstone, and the cherty Kaibab ("Upper Aubrey") limestone succeed one another in the order given and belong to the Pennsylvanian series (upper Carboniferous). These four formations furnish a record of continuous marine sedimentation in waters often very shallow and at no time very deep. After the cherty Kaibab limestone was deposited the region was raised above the sea without appreciable tilting and that formation was subjected to erosion which apparently operated only long enough to produce a youthful topography. Upon this surface were laid down without apparent discordance in dip the red sandstones and shales of the Moencopie formation, considered Permian, representing fluviatile or shallow-water deposits. Then followed the deposition of the Triassic sandstones, shales, and marls, which are separated from the Moencopie formation by a slight unconformity due to erosion, without marked discordance in dip. The great diversity, both laterally and vertically, in the composition of these beds, the presence in them of many petrified trees, and a land fauna at a certain horizon indicate that they are continental deposits—that is, they were laid down on a land surface. The Triassic rocks furnish the last record of sedimentation in this region, but a study of the surrounding country shows that deposition continued much longer and that Jurassic, Cretaceous, and possibly Eocene strata once covered the area. These strata, however, have since been entirely removed by erosion.

SEDIMENTARY ROCKS.

OCCURRENCE AND GENERAL SECTION.

The sedimentary rocks within the lava field are exposed at but four localities—at and near Garland Prairie south of Maine, a small town on the railroad between Flagstaff and Williams, and at Marble Hill, Slate Mountain, and Elden Mountain. At these localities only Carboniferous strata are exposed, and it is therefore necessary to study the younger formations either on the border of or beyond the lava field. The strata in general dip less than 1°, except where they are locally disturbed by monoclinal folding or the intrusion of igneous rock, and over the greater



GENERAL GEOLOGIC MAP OF THE SAN FRANCISCAN VOLCANIC FIELD AND VICINITY, ARIZONA

Base compiled from U. S. Geological Survey Atlas sheets

Scale $\frac{1}{500,000}$

5 0 5 10 15 20 25 30 Miles

Contour interval 1,000 feet

1913

Geology by H. H. Robinson
Surveyed in 1903

part of the region this dip is northeastward. The thickest continuous sections are exposed on the flanks of the laccoliths; elsewhere, on account of the horizontality of the strata, the exposures are much thinner, although in the walls of Oak Creek canyon 1,500 feet of beds appear in vertical section. The generalized section for the entire region has an approximate thickness of 2,500 feet.

Generalized section of sedimentary rocks in San Francisco Mountain region of northern Arizona.

System and series.		Group.	Formation.	Estimated thickness.	Lithologic character.
Quaternary.				*Feet.*	Alluvium. Moraines which may be of Wisconsin age.
Triassic.			"Leroux formation."	400	Light-colored shales (white, bluish, and pink), with some sandstone and calcareous beds.
Triassic.		Shinarump.	"Lithodendron formation." "Shinarump" conglomerate at base.	365 (35–50)	Sandstone, light-colored shales, and "marls." Conglomerate containing much petrified wood.
			Unconformity		
Carboniferous.	Permian.(?)	Shinarump.	Moencopie formation.	280	Red to light-brown shales, with some sandstone and calcareous layers.
			Unconformity		
Carboniferous.	Pennsylvanian.	Aubrey.	Kaibab ("Upper Aubrey") limestone.	375	Cherty limestone.
Carboniferous.	Pennsylvanian.	Aubrey.	Coconino ("Upper Aubrey") sandstone.	435–610	Cross-bedded white or light-yellow sandstone.
Carboniferous.	Pennsylvanian.	Aubrey.	Supai formation ("Lower Aubrey" sandstone and shale).	670	Red sandstone and shale.
Carboniferous.	Mississippian.		Redwall limestone.	250+	Massive gray limestone.

PALEOZOIC FORMATIONS.

The Paleozoic era is definitely represented by four conformable formations, all Carboniferous. They are, in order of deposition, the Redwall limestone, the Supai formation ("Lower Aubrey"), the cross-bedded white Coconino ("Upper Aubrey") sandstone, and the cherty Kaibab ("Upper Aubrey") limestone. The Moencopie formation is tentatively referred to the Permian because on lithologic and stratigraphic grounds it appears to be clearly correlated with the Permian of Kanab Creek, on the north side of the Grand Canyon in Utah.

REDWALL LIMESTONE.

The upper parts of the Redwall limestone, which at the type locality in the walls of the Grand Canyon, 60 miles to the north, has a total thickness of about 1,000 feet, are found on the east flank of Elden Mountain and at Marble Hill. At both places the limestone has been upturned by igneous intrusion and for the entire thickness exposed, about 250 feet at each place, has been changed by contact metamorphism to a pure white medium-grained marble. The strata exposed at Marble Hill consist throughout of pure limestone. At Elden Mountain, close to the contact with the igneous rock at the northwest corner of the eastern sedimentary area, the limestone becomes thinner bedded than usual and gives way to red calcareous shale and sandstone. The limestone immediately overlying these beds contains many fragments of shale and includes at one point a patch of conglomerate containing angular to subangular pebbles of quartzite from one-fourth to one-half inch in diameter.

A specimen of marble from Elden Mountain analyzed by F. N. Guild, of the University of Arizona, has the following composition:

Analysis of marble from Elden Mountain.

SiO_2	0.30
Al_2O_3, Fe_2O_3	.62
$MgCO_3$	3.25
$CaCO_3$	96.58
	100.75

The analysis shows that the specimen is a very pure limestone, which may be regarded as typical of the formation in this vicinity.

Poorly preserved fossils are found in the marble, of which the following from the uppermost strata at Elden Mountain have been very kindly determined by Prof. Henry S. Williams, of Cornell University:

Spirifer forbesi near increbescens (Hall's species in Iowa report).
Derbyia keokuk.
Orthis (small species).
Corals (species?).

On lithologic and stratigraphic grounds these beds are without question correlated with the Redwall limestone of the Grand Canyon. The age of the upper part of this formation is Pennsylvanian (upper Carboniferous). The lower part, which is not exposed in the region, is of Mississippian (lower Carboniferous) age.

The purity of the limestone and the character of the fossils indicate that the formation was deposited in oceanic waters, presumably of greater depth than 100 fathoms, as in general shore material is absent. The presence, however, of local bands of shale grading into limestone and of conglomerate containing angular to subangular pebbles shows that conditions of sedimentation were not uniform. These changes, according to prevailing ideas, would be interpreted as showing fluctuations in the elevation of the ocean bottom which at one period brought it within the littoral zone and permitted the deposition of the shale and conglomerate. Recent studies [1] have shown, however, that certain conditions of erosion on the land would allow the material that formed limestone to be deposited in waters of less than oceanic depth and that changes in the character of the sediments may be due to climatic variations.

AUBREY GROUP.

SUBDIVISIONS AND NOMENCLATURE.

New geographic names have recently been introduced by N. H. Darton [2] for the subdivisions of the Aubrey group, which is typically developed in northern Arizona. The use of the term Aubrey to cover the group and also to designate its several subdivisions is contrary to Survey rules of nomenclature, hence the necessity for the new names introduced by Darton, which will be used in this report, as follows:

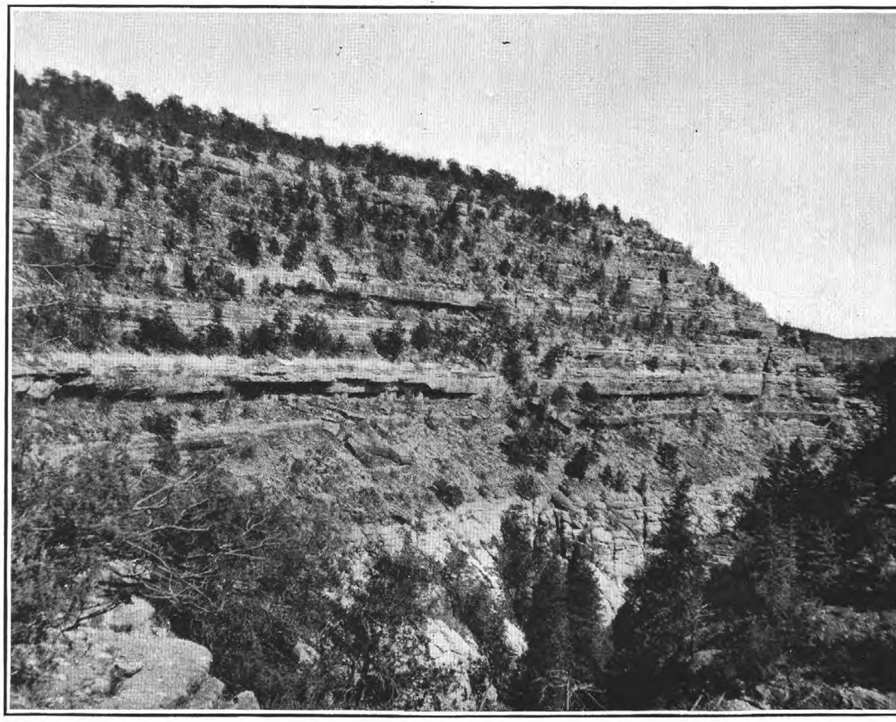
Kaibab limestone (replaces "Upper Aubrey" limestone).
Coconino sandstone (replaces "Upper Aubrey" sandstone).
Supai formation (replaces "Lower Aubrey" sandstone and shale).

The type localities of these formations are in northern Arizona, near the region covered by this report.

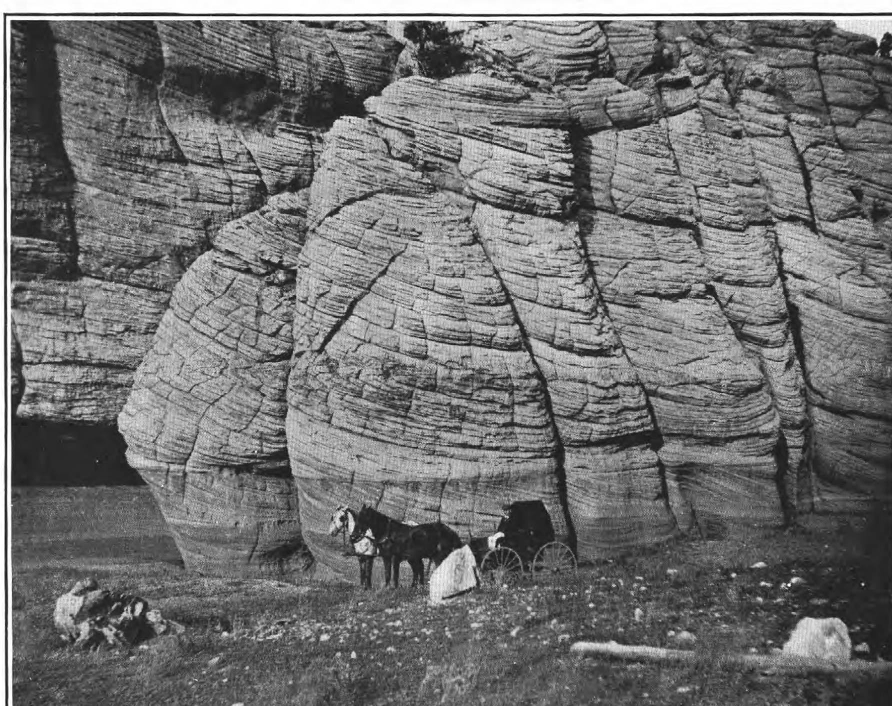
SUPAI FORMATION ("LOWER AUBREY" RED SANDSTONE AND SHALE).

The Supai formation outcrops in the lower walls of Oak Creek canyon and is the surface rock in that part of the Verde Valley between Oak and Sycamore creeks known as "the Red Rock country." It is also found on the eastern flank of Elden Mountain and at Marble Hill.

[1] Barrell, Joseph, Relations between climate and terrestrial deposits: Jour. Geology, vol. 16, 1908, pp. 159–190, 225–295, 363–384.
[2] Darton, N. H., A reconnaissance of parts of northwestern New Mexico and northern Arizona: Bull. U. S. Geol. Survey No. 435, 1910.



A. CHERTY KAIBAB ("UPPER AUBREY") LIMESTONE AT CLIFF DWELLINGS IN WALNUT CANYON, SOUTHEAST OF FLAGSTAFF.



B. CROSS-BEDDED COCONINO ("UPPER AUBREY") SANDSTONE IN WALNUT CANYON, SOUTHEAST OF FLAGSTAFF.

At these localities it is throughout a rather poorly cemented, uniformly fine-grained sandstone, generally light red in color but locally white, and not uncommonly having a cross-bedded structure on a small scale. In Oak Creek canyon the upper portion of the formation has much the same character as at the points noted above and consists of many thin beds which tend to form graded slopes. In the bottom of the canyon, however, the strata are much thicker and more resistant, and according to J. W. Fewkes [1] the same conditions exist in the Red Rock country.

The difference in resistance to erosion shown by different parts of the formation depends closely on the nature of the cementing material. In the softer beds this material is predominantly calcareous; in the harder beds it is siliceous.

The thickness of the formation, as measured at Marble Hill, is 670 feet, although minor faulting due to laccolithic intrusion makes the measurement somewhat uncertain. It agrees very closely, however, with that observed by Gilbert [2] (600 feet) in the Aubrey Cliffs at a point 15 miles southeast of Bill Williams Mountain, where the strata are undisturbed.

The formation has been referred to the Supai ("Lower Aubrey") purely on lithologic and stratigraphic grounds, as no fossils were found in it. Its age is Pennsylvanian (upper Carboniferous), as determined by fossils occurring in intercalated beds of limestone at several localities in the Plateau country.

Uniform conditions of sedimentation in shallow water in this general region are shown by the homogeneous character of the formation. That the beds were laid down in the open sea appears to be proved by the limestone strata containing marine fossils at neighboring localities.

COCONINO ("UPPER AUBREY") SANDSTONE.

Extensive outcrops of the Coconino sandstone occur in the Aubrey Cliffs along the southern edge of the plateau, in the walls of Sycamore, Oak, and Walnut canyons, and at Marble Hill, Slate Hill, and Elden Mountain. The formation throughout is massive and made up of many beds of uniform whitish to light-yellowish sand cemented by silica. Its striking feature is cross-bedding, which extends through its entire thickness. This feature is illustrated in Plate IV, *B*, showing the upper 100 feet of the formation as exposed in the walls of Walnut Canyon. The dip of the cross-bedding planes ranges from zero to a maximum of 24° and is generally not tangent to the underlying surface of deposition. Its direction, as determined by a number of observations, is southward.

The thickness of the formation was measured at Marble Hill, where it is 435 feet, and at Oak Creek canyon, where it is 610 feet. The formation was measured by Gilbert [3] in the Aubrey Cliffs, at a point 15 miles southeast of Bill Williams Mountain, and was found to be 700 feet.

The formation is unfossiliferous, but is evidently of Pennsylvanian age, as it occurs between the Supai formation and the cherty Kaibab limestone, both of which, on the evidence of fossils, have been assigned to the Pennsylvanian.

The physical conditions under which these strata were laid down are believed to have been similar to those existing during the deposition of the Supai formation. The somewhat coarser texture and more strongly marked cross bedding indicate more powerful currents and possibly shallower water. It might be supposed that the formation was of eolian origin on account of the character of the stratification, but the observations made do not appear to support this idea. The plunging layers do not generally exhibit the tangency to the underlying surface commonly observed in eolian deposits; the maximum angle of dip—24°—is much less than the natural angle of slope for dry sand—about 33°—and suggests the presence of water. In the absence of conclusive evidence of its eolian origin, it seems reasonable to suppose that the formation is marine, as it lies between two formations of known marine origin. The correctness of this opinion is rendered more probable by the fact that the formation in the

[1] Archeological expedition to Arizona in 1895: Seventeenth Ann. Rept. Bur. Am. Ethnology, 1898, pt. 2, pp. 550–569.
[2] Gilbert, G. K., U. S. Geog. Surveys W. 100th Mer., vol. 3, 1875, p. 163.
[3] Op. cit., p. 163.

Zuni Mountains of New Mexico, where it has the same characteristics as in the San Francisco Plateau, contains several intercalated beds of limestone carrying typical marine fossils.[1]

KAIBAB ("UPPER AUBREY") LIMESTONE.

The Kaibab limestone is extensively exposed on the north, northwest, and southeast sides of the volcanic field, where it forms the surface rock of the San Francisco Plateau. It is also exposed as the uppermost formation in the face of the Aubrey Cliffs from a point west of Williams as far east as Oak Creek. Where it occurs within the lava field it forms the surface upon which the lavas rest. It thus seems probable that it underlies the larger part of the volcanic area.

The formation is extremely variable in composition, although, broadly speaking, it appears to show a transition from rather impure limestones at the base to much purer beds in the middle and again to increasingly impure beds toward the top. It was most probably deposited in very shallow waters. The chief adulterant of the limestone is silica. In the vicinity of Flagstaff the silica occurs in the form of chert nodules, from 1 to 3 inches in diameter, containing fossil sponges, and these nodules, as well as quartz geodes, are abundant in the upper part of the formation. On the east side of Anderson Mesa the rock is an arenaceous limestone; at Grand Falls, on the Little Colorado, it is even more impure and should probably be classed as a calcareous sandstone. The rock also contains, in addition to the silica, a highly variable and sometimes large amount of dolomite. These features are shown by the following analyses, by F. N. Guild, of specimens from the upper part of the formation in the vicinity of Flagstaff:

Analyses of the Kaibab limestone.

	1	2
SiO_2	72.21	20.56
Al_2O_3	1.82	2.70
Fe_2O_3	1.04	
$MgCO_3$	5.62	23.96
$CaCO_3$	18.60	52.90
	99.34	100.02

1. Canyon southeast of Flagstaff, near mouth of sewer.
2. Vicinity of Elden Mountain.

The formation as a whole is white to grayish in color and rests directly on the cross-bedded sandstone below. In its upper and lower parts it is rather thin bedded, but near the middle it includes two or more beds that are 10 to 25 feet thick, and this sequence appears to be fairly constant in the southeastern part of the region (Pl. IV, *A*).

At no point was the entire thickness of the formation seen. The upper surface is generally one of erosion, and at localities where the contact with the overlying formation is found that with the underlying formation is hidden. The greatest thickness of the limestone is exposed on the east and west sides of Anderson Mesa. On the west side, at a point 2 miles south of the Ice Caves, the measured thickness is 340 feet. The full thickness, estimated from the restored section, is believed to be not more than 375 feet. Other measurements, made in Oak Creek canyon, in the shallow canyon 2 miles south of Hull Mountain, on the north flank of Elden Mountain, and at Marble Hill, range from 220 to 320 feet, the average being 260 feet. It would appear, therefore, that about one-third of the formation has been removed by erosion.

Fossils occur in all parts of the formation, and the characteristic ones have been described [2] as—

Productus ivesii.
P. semireticulatus.
Spirifer lineatus.
Aviculipecten, species closely allied to A. occidentalis.
Athyris sublilita.
Meekella striatocostata.
Hemipronites (species?).

[1] Dutton, C. E., Mount Taylor and the Zuni Plateau: Sixth Ann. Rept. U. S. Geol Survey, 1885, p. 132.
[2] U. S. Geog. Surveys W. 100th Mer., vol. 3, 1875, p. 177.

Frech [1] has described the following fossils from Walnut Canyon, southeast of Flagstaff:

Productus ivesii (very common).
P. aff. scabriculus (rare).
Spirifer (Martinia) lineata (rare).

On this evidence the formation has been assigned to the Pennsylvanian (upper Carboniferous) epoch.

COMPARISON OF PENNSYLVANIAN FORMATIONS IN SOUTHERN PLATEAU COUNTRY.

The red sandstone of the Supai formation, the cross-bedded Coconino sandstone, and the cherty Kaibab limestone, which comprise most of the Pennsylvanian of the southern Plateau country, appear to be sufficiently different from one another to permit a comparison between sections measured at several points. Observations are as yet much too scanty and the sections far too scattered to permit any exact conclusions, although they appear to furnish a basis for one or two reasonable inferences.

The sections measured at the following localities will be used: (1) Generalized section, San Franciscan volcanic field; (2) Hance trail, at the Grand Canyon of the Colorado [1]; (3) Kanab Creek section on north side of Grand Canyon [2]; (4) mouth of Grand Canyon at Grand Wash [3]; (5) Zuni Mountains in New Mexico.[4] The distances and directions in which the sections lie from the central part of the San Franciscan volcanic field are as follows: Hance trail, 65 miles north; Kanab Creek, 110 miles north-northwest; mouth of Grand Canyon, 150 miles west-northwest; Zuni Mountains, 200 miles east.

Thickness of formations of the Aubrey group.

	1	2	3	4	5
Kaibab limestone	375	a 500	800	a 200	400
Coconino sandstone	610	400	50	300	
Supai sandstone	670	1,000	1,455	800	800

a Top eroded.

The cherty Kaibab limestone decreases noticeably in thickness both southward and westward from Kanab Creek. It is possible that the thinness of the limestone at the mouth of the Grand Canyon is due entirely to erosion, although this does not appear probable in view of the fact that not more than half of the formation has been so removed in the San Franciscan volcanic field. The cross-bedded Coconino sandstone, on the contrary, increases very markedly southward and westward from Kanab Creek, whereas the red sandstone of the Supai formation decreases in all directions from the same point.

In the Zuni Mountains the red sandstone of the Supai formation preserves its individual character, but the cross-bedded Coconino sandstone and cherty Kaibab limestone are no longer distinct from each other and are included by Dutton [5] in one formation, which he describes as follows:

> The upper Aubrey is composed largely of sandstones. In color they are yellowish brown and the cement, instead of being calcareous, is siliceous, in fact, a regular chert. These sandstones are often conspicuously cross-bedded. * * * Intercalated with them are three or four thick beds of pure limestone containing an abundance of fossils of many and characteristic species.

The formation is evidently very similar to the Coconino ("Upper Aubrey") sandstone as it occurs in the western part of the Plateau country, except for the limstone strata. The absence of the cherty Kaibab limestone may be explained by erosion, by the thinning out of the formation, or by loss of identity through a change in the nature of the material. It is probable

[1] Frech, F., Compt. rend. 5th sess., Cong. géol. internat., 1891, p. 478.
[2] Walcott, C. D., Am. Jour. Sci., 3d ser., vol. 20, 1880, pp. 221-225.
[3] Gilbert, G. K., op. cit., p. 162.
[4] Dutton, C. E., op. cit., Pl. XVI, opposite p. 136.
[5] Op. cit., p. 133.

that the explanation lies in the last two causes. It was noted in the preceding description of the formation that the strata at Grand Falls, on Little Colorado River, are arenaceous and should be classed as calcareous sandstones. Likewise at Coon Mountain, a point farther east than Grand Falls, the formation, according to Barringer,[1] consists of "200 to 350 feet of yellowish-gray calcareous sandstone, which when eroded and weathered has the appearance of a limestone." It is evident, therefore, that the formation becomes more arenaceous in an easterly direction. Marvine[2] observed the upper members of the formation in the vicinity of Sunset Pass, 25 miles southeast of Canyon Diablo, but states that on Silver Creek, south of Holbrook, a point still farther east, "the overlying cherty limestone was not observed." It apparently loses its identity, then, as a limestone formation in the region between Clear and Silver creeks.

The cherty limestone is about two-thirds as thick at Coon Mountain as it is farther west. But a well record at Winona,[3] a station on the railroad west of Canyon Diablo, shows that the cross-bedded sandstone has decreased in thickness to 456 feet, compared with 610 feet in the San Franciscan volcanic field. Thus it would seem as if both the cross-bedded sandstone and cherty limestone become thinner to the east and coalesce, constituting one formation, 400 feet thick, in the Zuni Mountains.

The facts above stated possibly indicate the deposition of the two formations on a continental shelf whose shore line was situated east of the Zuni Mountains. It is at present difficult to interpret the alternate thinning and thickening of the three Pennsylvanian formations from the vicinity of Kanab Creek southward. The first inference would be that this locality was offshore and that the sea became shoaler toward the south. This view seems to be opposed by the fact that the Pennsylvanian rocks in southern Arizona are predominantly represented by a limestone formation concerning which Ransome[4] says:

> [It] was deposited in moderately deep water at some distance from the shore. * * * During certain stages of the accumulation of the limestones offshore currents carried some of the finest of the land waste into this area of tranquil deposition and left records of these occasional incursions in the form of pink shales.

TRIASSIC AND PERMIAN (?) ROCKS.

The Shinarump group, which in this area is for the present divided into the Moencopie formation, the "Lithodendron formation," and the "Leroux formation," is mapped as "Triassic and Permian(?)." The Moencopie formation is believed to be Permian; the others are Triassic.

SHINARUMP GROUP.

The Shinarump group is exposed at several localities near the edge of the lava field, as in the vicinity of Flagstaff, on the north and east sides of Anderson Mesa, in the walls of Sycamore Creek canyon, in the face of the mesa about Cedar Ranch, and east of the lava field, where it in part forms the surface rock of the Little Colorado Valley.

The most complete section observed (given below) is in the outliers and face of the mesa, mostly about half a mile south-southeast of Cedar Ranch, the locality containing the outcrop of petrified wood. Divisions 1 and 2 occur in the low hills at the northeast corner of the mesa; the others are in the face of the mesa a short distance south. The section is broken between divisions 2 and 3, but has been adjusted so as to be continuous. The base of the section is the cherty Kaibab limestone, upon which the shales rest in apparent conformity.

Section near Cedar Ranch.

	Feet.
10. Basalt. Rests on eroded surface	50
9. Alternating pale-red, pale-lavender, or gray shales and sandstones in strata from 10 to 20 feet thick. All weather easily. Upper part not clearly exposed	135
8. Whitish to pale-reddish firm sandstone	25
7. Whitish to pale-reddish, rather soft arenaceous shale, in places conglomeratic and containing a small amount of petrified wood	85

[1] Barringer, M., Coon Mountain and its crater: Proc. Acad. Nat. Sci. Philadelphia, vol. 57, pt. 3, 1905, pp. 864-865.
[2] Marvine, A. R., U. S. Geog. Surveys W. 100th Meridian, vol. 3, 1875, p. 213.
[3] Barringer, M., op. cit., p. 865.
[4] Ransome, F. L., The geology and ore deposits of the Bisbee quadrangle, Arizona: Prof. Paper U. S. Geol. Survey, No. 21, 1904, p. 46.

	Feet.
6. Light-gray slightly arenaceous marl	85
5. Yellowish to white medium to coarse grained sandstone containing rounded pebbles up to 3 inches in diameter, many angular fragments of petrified wood, and in places an entire section of a tree	35
	365
4. Red shales with a mottled red and gray calcareous clay layer 2 feet thick and a gray calcareous sandstone 6 inches thick at the base. The clay contains 68 per cent and the sandstone 75 per cent of material insoluble in hydrochloric acid	70
3. Red shales; at base several layers of gray calcareous shale from half an inch to 8 inches in thickness, of which 64 per cent is insoluble in acid	25
2. Light-brown to dull-red soft shales, with a few harder beds. All thin and weather easily. At base is a layer of gray calcareous sandstone 1 foot thick, of which 60 per cent is insoluble	85
1. Bright-red shales, strongly ripple marked; in upper part is a thin stratum of white fine-grained calcareous sandstone, somewhat cross-bedded	100
	280
Total thickness of section	695

The strata throughout are horizontal and no unconformities due to erosion were observed. The small area of the exposures would make the observation of such unconformities unlikely in any locality. The section is rather clearly divisible into two parts. The lower 280 feet consists of red and brown shales, in places arenaceous, containing a number of thin intercalated calcareous beds; the upper 365 feet is made up of much lighter colored marls, arenaceous shales, and sandstones, at the base of which is a coarse sandstone containing many pebbles and much petrified wood. The significance of these features will be discussed later.

At Flagstaff not more than 25 feet of red shale is present between the capping basalt and the Kaibab limestone, but on the south slope of the mesa, 2 miles northeast of town, the thickness increases abruptly to 150 feet. Red shales form the lower part of the section at this point and red sandstones the upper part. The difference in the thickness of the beds in this vicinity is due to irregularities in the surface of the underlying cherty limestone and represents an unconformity by erosion.

The composition of the rock from the quarry northeast of Flagstaff, which shows it to be a slightly calcareous sandstone, is as follows:[1]

Analysis of rock from quarry northeast of Flagstaff.

SiO_2	79.19	MgO	3.20
Al_2O_3, Fe_2O_3, FeO	3.75	CaO	7.76
		H_2O (or loss)	3.26
			97.16

On the east side of the north end of Anderson Mesa a thickness of about 400 feet of red shales and sandstones is exposed, and at the base is 5 feet of fine-grained red conglomerate. The upper part of the section is weathered to a fairly well-graded slope, but from the large quantity of pebbles near the top it is evident that a conglomerate corresponding to division 5 of the Cedar Ranch section is present, although petrified wood does not occur at this point. A quarter of a mile farther south the thickness of the section has increased to 550 feet, which indicates an unconformity by erosion without discordance of dip.

In the upper walls of Sycamore Canyon from 300 to 400 feet of the red beds are exposed. At the top of the section, on the east side of the canyon, is a conglomerate which from its position must be the same stratum that is seen at the other localities. The relation of these red beds to the Kaibab ("Upper Aubrey") limestone was not determined, but they owe their preservation partly to being faulted down into the underlying formations. This is the southernmost exposure of the Shinarump group thus far recorded in the southwestern part of the Plateau country.

[1] Merrill, G. P., Stones for building and decoration, 1903, p. 420.

COMPARISON AND CORRELATION OF TRIASSIC AND PERMIAN (?) FORMATIONS.

A comparison of the several exposures of the post-Aubrey formations in the San Franciscan volcanic field shows that they are all rather similar. In each the lower portion consists of red and brown shales, with local sandstones, which at Cedar Ranch contain a number of thin intercalated layers of a calcareous nature; the upper portion is made up of light-colored marls and sandstones and is separated from the lower portion by a conglomerate locally containing many fragments of petrified wood. The upper part is also somewhat gypsiferous, at least to a greater extent than the lower.

This general sequence agrees very closely with that of the sections of corresponding stratigraphic position observed by Gilbert,[1] Walcott,[2] and Dutton [3] in the region north of the Grand Canyon, and by Ward [4] in the Little Colorado Valley, and leaves little doubt as to their equivalence. That portion below the conglomerate containing the petrified wood ("Shinarump" conglomerate) is therefore correlated with the Permian of Walcott's Kanab section and the Moencopie formation of Ward. The upper portion belongs to the "Lithodendron formation" and the "Leroux formation," which are of Triassic age.

On the strength of the fossil evidence discovered by Walcott at Kanab Creek in 1879 the strata lying between the cherty Kaibab limestone and the "Shinarump" conglomerate, at the base of the "Lithodendron formation," have been tentatively referred to the Permian wherever they have been found in the southern Plateau country. It may be noted, also, that this formation (Moencopie) is separated from those below and above by erosional unconformities without notable discordance of dip, and that the upper unconformity, originally observed by Walcott at Kanab Creek, has also been recorded by Dutton and by Davis.[5] More recently Ward,[6] as the result of studies in the Little Colorado Valley, has referred these beds to the Triassic. This conclusion is based on a transition, which he observed at several points, between the Moencopie and the overlying "Lithodendron formation," and on the fact that although a "marked unconformity" exists between the underlying Kaibab limestone and the Moencopie formation, none was observed by him between the Moencopie and the "Lithodendron formation." There appears to be sufficient agreement among observers as to the general sequence of the strata above the Kaibab limestone, and doubt is expressed only as to the age of the Moencopie formation. The divergence of opinion has evidently arisen through the different viewpoints from which the problem is regarded—one lithologic, the other paleontologic. Of the two it seems as if the latter should be given the greater weight at present. Most of the unconformities in this part of the Plateau country are those due to erosion without any notable discordance in dip, and they may represent either a great or a small stratigraphic break, the determination of whose extent depends almost entirely on fossil evidence. In the absence of such evidence, therefore, no particular significance can be attached to the presence or apparent absence of such an unconformity.

ORIGIN OF TRIASSIC AND PERMIAN (?) FORMATIONS.

The Moencopie formation (Permian?), with its red and brown shales and sandstones, here and there extensively ripple marked, containing some gypsum and thin lens-shaped beds of a calcareous nature, is considered as being a very shallow water deposit in an arid to semiarid region. The area of observation, however, was not sufficiently extended to permit a conclusion as to whether it is fluviatile or estuarine in origin. At Cedar Ranch the intercalated calcareous beds become increasingly arenaceous toward the top of the formation, and this is interpreted as indicating a progressive shoaling of the waters in which the sediments were

[1] Gilbert, G. K., U. S. Geog. Surveys W. 100th Mer., vol. 3, 1875, p. 160.
[2] Walcott, C. D., The Permian and other Paleozoic groups of the Kanab Valley, Arizona: Am. Jour. Sci., 3d ser., vol. 20, 1880, pp. 221-225.
[3] Tertiary history of the Grand Canyon district: Mon. U. S. Geol. Survey, vol. 2, 1882, Chapter II.
[4] Ward, L. F., Geology of the Little Colorado Valley: Am. Jour. Sci., 4th ser., vol. 12, 1901, pp. 401-413.
[5] Davis, W. M., An excursion to the Plateau province of Utah and Arizona: Bull. Mus. Comp. Zool. Harvard Coll., vol. 42, Geol. Ser., vol. 6, No. 5, 1904.
[6] Op. cit., pp. 406-407.

deposited, a view that is supported by the character of the overlying conglomerate. The formation thins out southwestward from the Little Colorado Valley, and although this may be due to erosion, it is taken rather to point to the location of a shore line, or land area capable of supplying waste for the sediments, in southwestern Arizona beyond the present boundary of the Plateau. This view is supported by the change in the character of the intercalated beds from limestone at Kanab Creek to calcareous sandstones and other near-shore deposits at Cedar Ranch. (See p. 30.)

The overlying Triassic beds are predominantly, if not entirely, a continental deposit, as was suggested by Huntington and Goldthwait [1] in their description of the Triassic rocks near Toquerville, Utah. This conclusion is based on the character of the strata and their fossil contents. One of the striking features of the rocks is the great diversity of the material composing them, both horizontally and vertically. Ward's description [2] of the so-called "Shinarump conglomerate" (later changed by him to "Lithodendron formation"), which applies equally well to the overlying "Leroux formation," illustrates this point. He says:

> Although perhaps the most prominent feature of the Shinarump is the so-called conglomerate, which sometimes in truth deserves that name and contains somewhat large but always well-worn pebbles and cobbles derived from the underlying formations, still it rarely happens that this aspect of the beds constitutes the major portion of them. In the first place, the conglomerate tends to shade off into coarse gravels and then into true sandstones. They are, moreover, always more or less cross-bedded and usually exhibit lines of pebbles running through them in various directions. Although the sandstones generally occur lower down, still there is no uniformity in this arrangement, and the sandstones are often found in the middle and conglomerates more rarely at the top. But in addition to these the Shinarump conglomerate embraces other classes of beds. There is a well-stratified layer of thinnish sandstone shales that is often seen immediately under the heavy sandstone cap. Some of these shales have a grayish color and are highly argillaceous. These layers tend to thicken even within the formation itself, but especially farther out, and what is more significant, they often become transformed into a bluish-white marl. In the Petrified Forest region, where the Shinarump conglomerate attains its maximum thickness of 700 to 800 feet, this tendency on the part of certain beds to become transformed into marls is the most marked feature of the formation. The marls here occupy much more than half of the beds. They are very varied in color, showing besides the white and blue tints a great variety of darker ones, such as pink, purple, and buff. These heavy marl beds are interstratified between conglomerates, coarse gravels, and cross-bedded sandstones. * * * It thus becomes necessary to include under one designation all these varying beds which often change the one into the other at the same horizon within short distances. * * * In the lower Little Colorado Valley there occur numerous somewhat calcareous clay lenses, the lime taking the form of bright white stripes, while the clay is usually purple or pink. These are very distinct objects and vary in size from lenses 10 or even 20 feet in length to small lenticular blocks or somewhat oval or even spherical clay balls or pellets.

Vertebrate fossils have been found only in the lower portion of the "Leroux formation," which is about 400 feet thick. They consist of fragmentary remains of a labyrinthodont, two species of belodont, a dinosaur, and a cotylosaurian (*Placerias hesternus*). Concerning the last, Lucas [3] says: "Indications are that Placerias was a creature largely if not entirely terrestrial in habit."

The same statement may be applied to the dinosaur, referred by Lucas [4] to Palæoctonus Cope. The exact habitat of the labyrinthodont and belodonts may be a matter of doubt, but in all probability it was either fresh-water streams or swamps.

Petrified wood occurs throughout the "Lithodendron formation" and the "Leroux formation" but is most abundant in the sandstone overlying the variegated marls in which the vertebrate fossils are found. In the North Sigillaria forest, discovered by John Muir 9 miles north of Adamana, many trees are actually in place, a fact, of course, that bears only one interpretation. South of Adamana are three forests separated from one another by intervals of several miles, and to the west is a fourth forest. Fossil trees are very abundant in all these other forests, but none are in place. It seems not improbable that this local concentration of fallen

[1] Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in the Toquerville district, Utah: Bull. Mus. Comp. Zool., Harvard Coll., Geol. Ser., vol. 6, No. 5, 1904, pp. 210–213.

[2] Op. cit., p. 406.

[3] Lucas, F. A., A new batrachian and a new reptile from the Trias of Arizona: Proc. U. S. Nat. Mus., vol. 27, 1904, pp. 193–195.

[4] Lucas, F. A., Paleontological notes: Science, vol. 14, 1901, p. 376.

trees in closely adjacent areas is to be attributed to log jams in a river course, an idea suggested by Veatch's description of the "Great Raft" of Red River in Louisiana.[1]

POST-PENNSYLVANIAN LAND AREA OF SOUTHWESTERN ARIZONA.

It will be recalled that the Mississippian and Pennsylvanian formations of the San Franciscan volcanic field are supposed to have been deposited in a sea whose depth was becoming in a general way progressively less. At the end of Pennsylvanian time the area became a land surface, was slightly eroded, and had laid upon it the Moencopie formation (Permian?). The thinning out of this formation toward the southwest and certain changes in the character of the strata indicate that the waste-supplying land area was situated in southwestern Arizona beyond the present boundary of the Plateau.

The most interesting evidence on this point, however, is furnished by the pebbles in the conglomerate at the base of the "Lithodendron formation." In Sycamore Canyon, at the southern edge of the Plateau, many pebbles are distinctly subangular and are composed of gneiss, jasper, and other metamorphic rocks as well as basic igneous rocks of granitic texture. Fairly rounded cobbles of sandstone and chert up to 8 inches in diameter are less abundant. The greater part of them represent rocks of the same character as are exposed to-day in the Bradshaw Mountains. At Cedar Ranch, 40 miles north, there is a notable difference both in the shape of the pebbles and in the variety of rocks composing them. They are well rounded and have been derived mainly from strata that are now exposed only in the Plateau country.

Rocks similar in nature to those forming the mountain ranges to-day were thus exposed in southwestern Arizona, beyond the boundary of the present plateau, at the beginning of Triassic time. Areas of the upper formations of the Aubrey group were present in the same region, although the subordinate part played by pebbles from these formations in the conglomerate at Sycamore Canyon would seem to indicate that they did not originally extend much farther southwest than the present position of the Verde Valley; or that if they did cover a larger area, they were of only slight thickness. The subangularity of many of the pebbles in the conglomerate at Sycamore Canyon indicates that the source of material was close at hand.

A portion of southwestern Arizona of unknown extent was, therefore, a land area of sufficient elevation to supply large quantities of waste to the lower-lying country on the north during Triassic time and in all probability during Permian time. It was very probably a land area for a much longer period, as the following quotations indicate:

Ransome[2] describes the conditions existing at this time at Globe, Ariz., as follows:

> The upper Carboniferous limestone is the latest Paleozoic deposit of which the region preserves any record. If marine conditions continued into the Permian the deposits of that period must have been wholly removed before the strata were broken up and invaded by diabase. Had Permian or later beds been involved in that structural revolution some trace of them would probably have been preserved in resulting intricate lithologic mosaic.

Concerning the region about Clifton Lindgren[3] says:

> The time interval between the [end of the] Carboniferous and the middle of the Cretaceous is not represented by any sediments; there is, on the contrary, evidence of an epoch of erosion, for the Cretaceous rests unconformably on the lower Carboniferous at Morenci, where the upper Carboniferous is not present.

Similar conditions at Deer Creek are described by Campbell[4] as follows:

> Resting on the Pennsylvanian limestone at every point at which it is exposed in this field is a series of greenish-gray sandstone and shale beds which contain coal. * * * At most points these beds appear to rest conformably upon the Pennsylvanian limestone, but in the middle field there is a visible uncomformity between the limestone and the overlying sandstone and shale.
>
> Although the evidence regarding the age of these beds is not entirely conclusive, there seems to be a general agreement that they belong to the Cretaceous system and presumably were deposited in the later stages of that period.

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[1] Veatch, A. C., Geology and underground water resources of northern Louisiana and southern Arkansas: Prof. Paper U. S. Geol. Survey, No. 46, 1906.

[2] Ransome, F. L., Geology of the Globe copper district, Arizona: Prof. Paper U. S. Geol. Survey No. 12, 1903, p. 109.

[3] Lindgren, Waldemar, The copper deposits of the Clifton-Morenci district, Arizona: Prof. Paper U. S. Geol. Survey No. 43, 1905, p. 94.

[4] Campbell, M. R., The Deer Creek coal field: Bull. U. S. Geol. Survey No. 225, 1904, p. 240.

Of the Bisbee region Ransome [1] says:

With the close of the Pennsylvanian epoch the long era of Paleozoic sedimentation * * * came to an end. Orogenic forces became dominant, and the region of the Bisbee quadrangle was elevated above sea level.

During Triassic and Jurassic time the mountainous country elevated by the post-Pennsylvanian deformation was subjected to erosion. If any sediments were deposited within the quadrangle during these periods they were removed prior to the opening of the Cretaceous and have left no record of their former presence.

It is evident that the Pinal schist contributed detritus to the basal beds [of the Cretaceous], but as it is probable that all the schist within the limits of the quadrangle was covered by the Glance conglomerate before any considerable part of the Morita beds was laid down, the land mass that furnished the sands and muds must have been outside the area under investigation. The main shore line probably lay to the west of the Mule Mountains.

The close similarity in the conditions existing at these localities, together with the evidence from the San Franciscan volcanic field, makes it quite certain that a land area existed in southwestern Arizona from the end of the Carboniferous period to the middle of the Cretaceous period. Whether this area has since been covered by the sea is difficult to decide; it has probably not been entirely submerged.

GLACIATION AND ALLUVIATION OF SAN FRANCISCO MOUNTAIN.

The former presence of a glacier in the large interior valley on the northeast slope of San Francisco Mountain [2] is clearly proved by moraines, an outwash plain, and polished rock surfaces. Closely related material also occurs on the north slope of the mountain. No glacial deposits were observed on the south, east, and west outer slopes. Instead, extensive and heavy deposits of alluvium in coalescing fans are present, as may be seen by reference to Plates V (p. 40) and VII, *B* (p. 42).

The character and distribution of the glacial deposits in the interior valley have been described by Atwood.[3] In brief these deposits consist of well-developed medial, lateral, and terminal moraines, a till sheet, and an outwash plain. The terminal moraine is situated 2 miles from the head of the valley, at an elevation of 9,200 feet. Above it the valley is occupied by many small dome-shaped hills with intervening swampy areas; below it the surface is comparatively smooth and thoroughly drained. At the head of the valley, under San Francisco Peak, rock surfaces have been somewhat polished and striated by the ice. On the whole, however, ice erosion appears to have been slight, as may be judged by the fact that the sides of the valley have the same uniform slopes above and below the terminal moraine. That is to say, there are no pronounced cirques at the head of the valley, nor are the walls noticeably oversteepened. The glacier at the time of its maximum extension had a length of 1¾ to 2 miles, a width at its lower end of half a mile, and a minimum thickness, estimated from the height of the terminal and lateral moraines, of 200 feet.

On the north side of the mountain is a deposit composed of the same material as the glacial deposits of the interior valley and the alluvial fans on the outer slopes. It grades into the fans along its lower (northern) side. This ridge of material has a length east and west across the slope of 1 mile and an average width of three-fourths of a mile. Its greatest thickness is estimated at 300 feet. The upper edge is in contact with the lava-formed slope of the mountain at a rather uniform elevation of 9,600 feet. The elevation of the lower boundary is variant, but gradually decreases from 9,000 feet at the east end to 8,700 feet at the west. It is clear that this material was not deposited by a glacier. As the interior valley, with its large catchment area, held a glacier only 2 miles long, the less favorably situated northern slope, with almost no feeding ground, could not have supported an ice sheet sufficient to bring down the amount of material now found at the foot of the mountain. Had glaciers existed on the north side of the mountain they would have been confined to the three large ravines and their moraines would be appropriately arranged about the mouths of the ravines. No such arrangement of moraines exists; instead the belt of material extends without change in form or direction across both

[1] Ransome, F. L., The geology and ore deposits of the Bisbee quadrangle, Arizona: Prof. Paper U. S. Geol. Survey No. 21, 1904, pp. 106-107.

[2] For a detailed description of San Francisco Mountain see pp. 40-53; for topographic map see Plate V (p. 40).

[3] Atwood, W. W., The glaciation of San Francisco Mountain, Arizona: Jour. Geology, vol. 13, 1905, pp. 276-279.

uneroded slope and ravine. The explanation of the origin of this moraine-like ridge is presumably to be found in such a process as solifluction.[1]

The outer slopes of San Francisco Mountain (Pl. V), as well as the other large cones of the region, are extensively and heavily mantled with alluvial deposits. The material of these alluvial fans is, on the whole, coarse and contains many angular fragments of disintegrated but unweathered lava. In general it is indistinguishable from the material composing the glacial deposits. The resemblance between the alluvial fans on the outer slopes and the glacial outwash plain of the interior valley is most striking. Especially significant is the gradation into the alluvial fans of the moraine-like ridge of material on the north slope. There can be little if any doubt that the most recent alluvial fans now seen on the outer slopes were formed at the same time, and consequently under the same climatic conditions, as the glacial deposits of the interior valley. The relation of the deposits on the north side of the mountain indicates, however, that the greater part of the alluviation of the outer slopes occurred before the glaciation of the interior valley. The estimate that 75 per cent of the material eroded from San Francisco Mountain is contained in the alluvial deposits on the slopes or about the base of the cone shows that there was a period of some length during which climatic conditions were favorable to alluviation, whereas it was only during the later part of this period that they were favorable to glaciation. In general the streams were not able to remove the waste supplied to them.

It may be concluded, therefore, that the alluvial fans, in part, were deposited when the climate was colder than at present and the precipitation was somewhat greater. The angular unweathered lava fragments in the alluvium show that rock disintegration was predominantly the result of frost action. The position of the fans, with maximum grades of 10°, well up on the slopes of the mountain clearly indicates the inability of the existing streams to remove the large amount of waste supplied to them. In general, the effect of the increased cold was to cause a much greater increase in the forces of erosion than in those of transportation.

It may be noted here that with the return of a warmer climate and possibly smaller rainfall, the conditions above described have been reversed. Transportation now overbalances erosion, and the alluvial fans are undergoing dissection. At many localities they are cut to their outer edges by numerous washes, and the eroded material is being redeposited beyond the original limits of the fans on lower and flatter slopes.

It will be seen that the three kinds of detrital deposits on San Francisco Mountain are closely related and that their mode of deposition depended primarily on the position of the locality where they occur with respect to the sun. Thus alluvium was deposited on the outer south, east, and west slopes, which were most exposed to the sun. On the less-exposed north slope a semiglacial deposit was laid down. In the interior valley, so situated as to receive the least direct sunlight, glacial conditions existed and the material was deposited by ice. Deposition was thus effected by water in the most exposed localities, by water and snow (or ice) in less exposed localities, and by ice in the least exposed situations.

The glacial deposits on San Francisco Mountain, in latitude 35° 20′ north, constitute one of the southernmost records of ice action within the United States. It will be interesting therefore, to try to form an idea of their age, especially in view of the relation between them and the alluvial deposits. The determination of the age of the deposits relative to that of the mountain appears simple, but correlation with glacial events as known elsewhere in this country must remain in the hypothetical stage because of the isolation of the locality.

It is most probable that the glacier occupied the interior valley of San Francisco Mountain at a time when it had very nearly its present size.[2] This is shown by the form of the valley and the distribution of the glacial material. If the valley were entirely the result of glacial erosion there should be moraines at its eastern extremity. There would also have been glaciers of considerable size on the outer slopes, evidences of which should exist in their moraines. That

[1] Andersson, J. G., Solifluction, a component of subaerial denudation: Jour. Geology, vol. 14, 1906, pp. 91–112.

[2] W. W. Atwood, in a personal communication, says: "I do not think that the ice is accountable for very much of the widening or deepening of the large interior valley of the mountain."

this would be so is clearly indicated by the glacial conditions now existing on Mount Shasta, Mount Hood, and Mount Rainier. No moraine was observed, however, in the interior valley below the one situated at an elevation of 9,200 feet, and no true glacial material was seen on the outer slopes of the mountain.

It may be concluded, therefore, as already stated, that the glacier occupied the interior valley at a time when it had practically its present size. This shows the recency of the glacier and its deposits, as well as the upper (younger) portion of the alluvial fans, both with respect to the age of the mountain and actually in geologic time. The freshness of the glacial material, even though climatic conditions have been conducive to a minimum of weathering, the undrained state of the till sheet and the slight dissection of the deposits all point to the existence of the glacier during the Wisconsin epoch, probably the late Wisconsin, of the continental ice sheet. A tentative estimate of the postglacial erosion and total erosion of the interior valley gave a ratio of 1:25. This is considerably greater than the ratio of 1:16 for the erosion since the late Wisconsin to that since the Kansan epoch, as suggested by Chamberlin and Salisbury.[1] If the age of San Francisco Mountain is correctly determined as early Pleistocene, this ratio of 1:25 points to the late Wisconsin age of the glacier.

GEOLOGIC STRUCTURE.

GENERAL CHARACTER.

The geologic structure of the part of the San Francisco Plateau treated in this report, and indeed of the entire region south of the Grand Canyon of the Colorado, is simple and duplicates the features in the district north of the canyon described by Dutton.[2] The simplicity extends only to the nature of the displacements and not to their interpretation, as has been shown by the recent work of Davis and of Huntington and Goldthwait. The movements have been expressed by both monoclinal and asymmetrical anticlinal folding and by normal faulting, but not so strongly as in the region to the north. As a rule, the folds have caused greater displacements of the strata than the faults, although the faults are more numerous.

FOLDS.

Elevations taken on the upper surface of the Kaibab limestone at a number of localities indicate that the main structural feature of the region may be called for descriptive convenience a very flat anticline. The elevations on which the existence of this fold is based are as follows:

Elevations showing anticlinal structure of San Francisco Mountain region.

	Feet.
Aubrey Cliffs, 11 miles west of Williams	6,400
Cataract Creek, 8 miles northwest of Williams	6,300
Garland Prairie	7,100
Norris Tanks	7,100
Flagstaff	6,900
Anderson Mesa, north end	6,800
Winona, 15 miles east of Flagstaff	6,300
Hull Wash, 2 miles east of Cedar Ranch	6,300
Hull Wash, 11 miles west of Little Colorado River	5,000
Grand Falls, Little Colorado River	4,500

The fold covers the entire field and its axis strikes N. 30° W., passing through Sitgreaves Peak. To the north this anticline dies out between the westward-dipping slope of the Coconino Plateau and the eastward-dipping slope from the Aubrey Cliffs. These slopes are structural in origin and give rise to the broad trough in which flows Cataract Creek. On the south the anticline is abruptly terminated by the Aubrey Cliffs. The slopes of the fold are very gentle

[1] Chamberlin, T. C., and Salisbury, R. D., Geology, vol. 3, 1906, p. 414.
[2] Dutton, C. E., Tertiary history of the Grand Canyon district: Mon. U. S. Geol. Survey, vol. 2, 1882.

in all directions. The dip of the eastern limb is less than 1° and is extremely uniform whatever the distance over which it is measured, as may be seen from the following table:

Dip of eastern limb of anticline.

	Minutes.
Flagstaff to Grand Falls, 32 miles	52
Cedar Ranch to Little Colorado Valley, 18 miles	48
Anderson Mesa to Angell, 12 miles	45
Anderson Mesa to Winona, 7 miles	48
Anderson Mesa at north end, 3½ miles	45
Anderson Mesa at north end, 1½ miles	52

From the summit of the fold to Flagstaff, about 18 miles, the slope is 10′ E., and from the summit westward to the Aubrey Cliffs, 22 miles, it is 20′ W. The slope of the crest of the fold can not be given, as observations are lacking, but it appears to be nearly horizontal as far north as Mount Sitgreaves, from which it pitches gently down to the level of the Cataract Creek trough. The slopes given above are the present slopes of the fold. If it was formed contemporaneously with the strongly-marked monoclines occurring elsewhere in this general region, it is probable that these are not the original slopes. Later faulting and regional warping may have somewhat changed the original attitude of the fold, but observations by which the effects of these later movements might be distinguished are lacking. The extreme uniformity of the eastern slope precludes the existence of faults of great magnitude in that region. The maximum difference in the slope measurements (7′) would cause a change in elevation between Flagstaff and Little Colorado River of but 350 feet, or about the thickness of the Kaibab limestone. This figure roughly represents the greatest possible displacement by faulting that would be likely to escape detection in the area considered. A fault of greater throw would cause either a noticeable break in the continuity of the surface or would bring other formations than the Kaibab limestone to the surface, and neither of these features was observed.

The Coconino fold, which bounds the Coconino Plateau, lies mostly outside of the area covered by this report, but it may be briefly described. This fold is, for the most part, an asymmetric open anticline. The dip of the southwestern limb (1½°) is, however, so much less than that of the northeastern limb (20°) and is so nearly parallel to the dip of the strata farther northeast that the fold assumes the character of a monoclinal flexure, as this term has been applied to displacements in the Plateau country. This may be seen by comparing the Coconino fold with the well-known Kaibab displacement, which adjoins it on the north; they have several features in common.

The steep limb of the Coconino fold is clearly defined for 25 miles from the rim of the Grand Canyon near Hance's cabin to Coconino Point, in the Little Colorado Valley, at first trending southeast and then gradually swinging around to the east. Throughout this distance the dip of the flexure is 20° to the east and north. The displacement produced by the flexure, measured on the Kaibab limestone, which is the surface rock of the plateau, is 100 feet at the rim of the canyon, but gradually increases until it is over 1,000 feet at Coconino Point. At the latter locality the flexure turns southward for 3 miles and then southwestward, and the dip of the strata increases to 45°. A rather symmetric eastward-pitching anticline is thus formed which is strikingly displayed through the stripping of the soft strata overlying the Kaibab limestone. (See Pl. II, *A*, p. 17.) The dip of the flexure (45° on the south side of Coconino Point) gradually decreases in a westward direction until in a distance of 15 miles it has flattened to 1½°. This is the dip of the southwestern limb of the Coconino anticline, and it prevails, with minor irregularities, throughout a belt of country some 15 miles wide, extending northwestward to the Grand Canyon in the vicinity of Bass's camp.

The sharp dip seen in the strata at Hance's cabin, on the south rim of the Grand Canyon, may be traced northwestward for over 8 miles in the canyon, as far as Shoshone Point. The direction of the flexure makes it certain that it is a continuation of the monocline described by Dutton[1] as associated with the West Kaibab fault. The disappearance of the flexure

[1] Op. cit., p. 128.

in the region north of the canyon, however, remains to be traced, as the structure is complicated by the monocline which crosses the Powell Plateau, 6 miles farther west.

At Black Point, on the west side of Little Colorado River, 8 miles below Black Falls, is a previously undescribed fold of considerable magnitude, which will be called the Black Point monocline. It appears to be a true monocline, as the strata on opposite sides of it have the same strike and dip. It may be traced from Black Point S. 15° W. for 10 miles, as far as Doneys Cone, where it disappears under recent basaltic lavas. The dip of the strata is 15° S. in this part of its course, but at Black Point it decreases to 5° and in the region to the north it flattens to less than 1° E., the normal slope of the surface.

The cherty Kaibab limestone forms the surface of the fold between Black Point and Doneys Cone and also covers a considerable area to the northwest, locally known as the "limestone mesa." Upon the back of the fold, resting on the cherty limestone, are striking isolated buttes of red shale. At Black Point, where the greatest thickness of folded strata has been preserved under a capping of basalt, the Kaibab limestone and the Shinarump group are involved in the displacement, but whether still younger formations are present was not determined. It is estimated that the vertical displacement that produced the monocline is not less than 800 feet at Black Point or more than 500 feet at Doneys Cone. The monocline appears, therefore, to flatten out to the west as it does north of Black Point, although at a gentler rate. On the whole, the Black Point monocline bears a strong resemblance to the Coconino fold, but the uplift that produced it was not so great, nor is it so distinctly marked topographically on account of the smaller extent to which the red beds overlying the cherty limestone have been removed. It may be noted also that the dip of the Black Point monocline is in the opposite direction from that of the Coconino fold.

The country between the Black Point monocline and Grand Falls, 20 miles farther south, is floored with the red shales and sandstones of the Moencopie formation, but at Grand Falls the Kaibab limestone again comes to the surface. This suggests that another, though smaller, fold may exist in this vicinity. It is not probable that the presence of the limestone is due to faulting.

In the White Mesa, on the north side of Hull Wash opposite Cedar ranch, another small fold may be observed. The southeast face of the mesa is a cliff caused by a fault having a trend of N. 25° E. At the point where the Grand Canyon wagon road passes around the north end of the cliff the Kaibab limestone, of which the mesa is composed, strikes N. 60° W. and dips 10° N. To the southwest the strata, having risen 400 feet, regain a horizontal position, which they maintain as far as the head of the wash 3 miles beyond, where they are buried under basaltic lavas. The fold was not traced northwestward, but appears to die out within a short distance, and south of Hull Wash no certain evidence of its existence was observed. The meager exposure of this fold makes it difficult to form a definite idea of its extent or magnitude. It seems likely from the location that it should be considered as associated with the strong Coconino fold to the east.

The Echo Cliffs monocline, east of the Kaibab Plateau, has been considered probably to continue southward nearly to Winslow, about 100 miles distant. A view of the Little Colorado Valley northeast of Coconino Point from a distance of 10 miles suggests another explanation. The Echo Cliffs topographic map shows that the country opposite the mouth of Moencopie Wash has a slope of 3° SE. The strata of the Shinarump group have a corresponding dip and can be traced in a southwesterly direction across the Little Colorado to the foot of Coconino Point. On account of the close dependence of the topography on geologic structure in this portion of the Plateau, this relation is considered to indicate that the Echo Cliffs monocline changes its direction from south to southwest near Moencopie Wash and loses its identity east of Coconino Point. If this supposition should prove correct, the gentle fold at Winslow should probably be correlated with the equally gentle San Franciscan anticline if any correlation is possible.

The evidence from the Coconino and Black Point folds assigns to them only a post-Triassic age. Dutton[1] found that the Echo Cliffs monocline, which he considered very nearly coeval

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[1] Op. cit., pp. 191, 205.

with the East Kaibab fold, involved Eocene strata along the southern border of the High Plateaus of Utah. He concluded that East Kaibab fold was formed in Pliocene time, shortly before the period in which the Grand Canyon originated. Davis,[1] however, has pointed out that the great retreat of the Vermilion Cliffs around the north end of the Kaibab Plateau since its uplift, as compared with the slight retreat of the upper walls of the Grand Canyon since the beginning of the canyon cycle, clearly indicates a greater age for the Kaibab and Echo Cliffs displacements. This view is supported by the observation of Walcott[2] as to the unfractured condition of the beds of the Aubrey group in the northern part of the East Kaibab monocline, from which he inferred a considerable thickness of overlying sediments at the time the fold was formed. It is probable that these folds originated during the Eocene-Miocene interval.

FAULTS.

None of the major faults of the northern part of the Grand Canyon district cross the San Franciscan volcanic field, although the fault which forms the western boundary of the field may prove on further study to be a southward prolongation of the Hurricane fault, offset to the east. It is not improbable, however, that the region is intersected by a considerable network of minor faults. A few such faults were observed, but no particular search was made for them, as they are difficult to detect. The older faults—those antedating the eruption of the basalt of the first period of volcanic activity—are the more difficult to locate because the relief produced by them was effaced during the peneplanation of the region. The younger faults, formed after the eruption of the basalt of the first period, but before the eruption of the basalt of the third period, may be successfully located in the area outside of the recent basalts, for the relief produced by them still remains. Within the area of the recent basalts they are hard to locate, although in a few places such features as the linear arrangement of the small basaltic cones may give a clue to their situation.

Only six faults were actually observed, but the presence of a number of others was recognized, especially near Oak Canyon. They are all located in the area of the older basalt or outside of the lava field. Five of the faults range in direction from N. 15° W. to N. 25° E., and the sixth trends N. 65° W., which is approximately the strike of several small faults east of Oak Canyon. As these were the only two general directions noted, the minor faults may prove to be grouped into two sets striking broadly north-south and east-west.

Dutton first called attention to the fact that practically all the major faults of the region north of the Grand Canyon have lowered the country on their west sides. The same is true of the fault which has given rise to the Aubrey Cliffs west of Williams. But of the five minor faults observed, including the Bright Angel fault at the Grand Canyon, four have lowered the region on their east sides.

The age of the faults can be fixed in relation to the periods of volcanic activity. They are all younger than the first and older than the third or last general period of eruption. (See p. 95.) This means that the faulting occurred after the great erosion of the Grand Canyon district had been completed and refers it to the canyon cycle. The faults are therefore of post-Pliocene age.

The faults are here described in order of magnitude. The scale of the general geologic map (Pl. III) is so small that it is impracticable to indicate them on it

The Aubrey Cliffs fault, west of Williams, where the wagon road to Ash Fork crosses it, has an average direction of N. 15° W. It may be traced in the escarpment to which it has given rise for over 10 miles southward, and it dies out in about the same distance to the north. The total throw is at least 1,000 feet to the west. The displacement is distributed between two faults, the eastern one having a throw of 250 feet, the western taking the remainder. In the face of the uplifted block near the top is exposed the Kaibab limestone, overlain by basalt of the first period of eruption, and the same lava is found on the dropped block to the west. There

[1] Op. cit., pp. 140-141.

[2] Walcott, C. D., Study of a line of displacement in the Grand Canyon of the Colorado in northern Arizona: Bull. Geol. Soc. America, vol. 1, 1889, p. 49.

has practically been no retreat of the strata to the east from the fault line, and this indicates the recency of the movement.

The Oak Canyon fault may be traced from Woody Mountain, 7 miles west-southwest of Flagstaff, for 16 miles along the course of the canyon to the Verde Valley, and is continued still farther south. Its trend is very straight and is true north and south. In the vicinity of Woody Mountain the fault has a throw of 600 feet to the east and is marked by a steep cliff. North of the mountain the cliff is not seen, and the fault apparently dies out before reaching the railroad, at what point can not be said, as the area is covered by more recent lava flows. As in the case of the Aubrey Cliffs fault, the uplifted block has been little dissected since the faulting.

The fault that produced the White Mesa, north of Cedar Ranch, strikes N. 25° E. and has a throw of not less than 400 feet to the east. From the south end, where it is obscured by more recent lavas, it was traced northward for 5 miles, but it has a much greater extension in that direction. The face of the mesa is slightly eroded and is cut by several small ravines; the fault line at its base is hidden by recent flows of basalt.

The fault on the north side of Clark Valley strikes N. 65° W., has a throw of 300 feet to the south, and in this locality marks the boundary of Anderson Mesa. The fault line is easily traceable on account of the difference in level of the Kaibab limestone and capping basalt on the two sides of the valley from Greenlaw's sawmill to the Ice Caves, beyond which it was not studied. The uplifted block appears to have suffered little erosion, but in the dropped block a shallow valley has been cut, which narrows somewhat and deepens at its north end, forming the head of Walnut Canyon.

Although it was not closely observed, there appears to be a fault of perhaps 300 feet throw to the east along the base of the Black Point monocline in the vicinity of Doneys Cone. It has the same direction as the fold, N. 15° E., but is probably of later age.

South of Coconino Point, near Hull Wash, are several faults, or a single fault of irregular course, with a throw to the west, that have brought the red shales of the Moencopie formation into contact with the cherty Kaibab limestone. This would indicate a throw of 300 to 400 feet. Where first observed near Hull Wash the direction of the fault was N. 45° E.

CHAPTER III.

GEOLOGY OF THE VOLCANOES AND LAVA FIELDS.

OUTLINE OF CHIEF EVENTS.

This chapter is devoted to the geologic phenomena of the volcanic region proper as they are displayed in the field. The igneous rock names are mostly simplified forms of those given in Chapter V, which have been based on characters determined in the laboratory. Brief descriptions of the rocks and the amounts of the principal chemical constituents are given for the general reader who may not be interested in the detailed petrographic descriptions found in Chapter V. The summation of the partial analyses is generally low; the difference between it and 100 per cent (more or less) indicates the amount of water, phosphoric pentoxide, and other minor oxides which are omitted.

As the volcanic phenomena are taken up, broadly speaking, in historical order, a brief outline of the chief events may be given. Three general periods of volcanic activity, separated by intervals of quiescence, occurred in the San Franciscan volcanic field. The phenomena of the first period were of a simple nature and consisted of widespread eruptions of basalt from small cones. During the second period various lavas, ranging from andesites to rhyolites, were erupted and built up a few large cones. This period was further marked by laccolithic and semilaccolithic intrusions contemporaneous with the volcanic extrusions. The third period closely resembled the first in that it witnessed the eruption of a single lava—a basalt—but it was characterized by the formation of a larger number of cones and a less widespread distribution of the lava.

FIRST GENERAL PERIOD OF ERUPTION.

The first general period of volcanic activity is represented by a basalt which covers an area much larger than the San Franciscan volcanic field. The lava occurs predominantly as flows; fragmental material, except in cinder cones, was observed only at Marble Hill in the form of rather fine ash and represents an initial stage of activity. The original volume of the erupted lava, obtained by multiplying a total area of 3,000 square miles by an estimated average thickness of 50 feet, is calculated to be 30 cubic miles. Scattered lava and cinder cones mark the positions of the vents at which eruptions occurred. In general the cones do not exceed 700 feet in height, although a few are over 1,000 feet. It is estimated that of the 300 basalt cones in the region 100 belong to the first period and 200 to the third period of eruption. A smaller proportion of cones is assigned to the first period because where only basalt of this period is present, as in the southwestern part of the field, cones are less numerous than in those areas where basalt of the third period occurs. Eruptions from fissures are indicated by the direct connection between dikes and flows in the walls of Oak and Sycamore canyons. Erosion has not been favorable, however, to the exposure of dikes, so that no idea can be formed as to the relative importance of this mode of eruption.

The flows commonly have a thickness of 25 to 75 feet and at no observed point do they exceed 200 feet. Along the southern edge of Switzer Mesa, near Flagstaff, the thickness is 15 feet, but to the north it appears to increase slightly. The general thinness of the flows seems unusual considering the large area they cover. It may be explained in part by the fact that most of the exposures are at the periphery of the field and consequently near the ends of the flows, the thicker central parts having been covered by more recent lavas. The flows, on the whole, do not have scoriaceous surfaces; normally they are dense throughout, and columnar structure occurs in both the thin and the thick flows. Presumably the lava must have had a high degree of liquidity to spread out so thinly over so large an area.

The flows are more or less disintegrated and their surfaces are covered by a mass of loose fragments embedded in a thin layer of soil. At some localities, however, considerable weathering of the lava has resulted in the formation of a residual clay.[1] Such an area south of Flagstaff has been described by F. N. Guild,[2] who says:

On the surface the country has the appearance of a rough lava bed with a minimum of soil. When this is removed, together with the fragments of lava, there is revealed a thin blanket deposit of pure red clay free from lava fragments and of a uniform thickness of about 22 inches. Below this deposit the material is similar but less thoroughly decomposed into clayey constituents. The uniformity of the clay deposit has led me to conjecture that frosts have had much to do in its concentration by bringing the undecomposed lava fragments to the surface. The presence of this deposit can be inferred in many places, where the loose lava fragments are not too numerous, by the deep cracks in the soil, some of which are an inch across and 1½ feet deep.

The basalt is typically very dark gray in color on fresh surfaces. An aphanitic groundmass, which occasionally might be considered microcrystalline, contains about 10 per cent of lusterless or iridescent olivine phenocrysts. The chemical composition is given by the following partial analysis:

Partial analysis of basalt of first period of eruption.

SiO_2	47.7	Na_2O	2.5
Al_2O_3	15.3	K_2O	.6
Fe_2O_3	5.9	CO_2	1.9
FeO	4.8	TiO_2	1.4
MgO	7.3		
CaO	11.8		99.2

The olivine is generally much altered, but as the rock is otherwise entirely fresh the calcite present must be an infiltration product.

The basalt rests on the Kaibab limestone in the western part of the field, except near Sycamore Creek, where the Shinarump group is present. In the area east of a line joining Anderson and Cedar Ranch mesas, approximately one-third of the region, the lava generally overlies the Shinarump group. The surface on which the lava rests is a peneplain, and observations at numerous localities show that the eruptions of the first period occurred when the peneplain was undissected.[3]

Where the basalt rests on the resistant Kaibab limestone erosion has been confined mostly to the cutting of canyons and has resulted in the removal of a minimum amount of lava. Where the lava rests on the soft strata of the Shinarump group it has been much reduced in area by undermining and now caps only the mesas and buttes which rise 200 to 1,000 feet above the surrounding country. This is well illustrated along the eastern boundary of the volcanic field, in the Little Colorado Valley, and at Cedar Ranch. It is strikingly displayed along the entire east side of the Black Mesa and may be seen on a smaller scale near Flagstaff, where the lava caps a mesa whose top is 50 to 200 feet above the Kaibab limestone, depending on the thickness of the intervening Moencopie formation.

It is estimated that the basalt originally covered 3,000 square miles in the San Franciscan volcanic field. As it now covers 2,200 square miles its area has been reduced more than one-fourth. The volume of lava removed is probably not more than one-fifth of the total, because erosion has been confined largely to the periphery of the field, where the flows are thinnest.

Similar basalts resting on a peneplain are widely distributed in the surrounding plateau country. They extend unbrokenly west and south of the area included within the San Franciscan field. The extent of the basalt to the west is unknown, but to the south, in the Black and Mogollon mesas, it covers more than 1,000 square miles. A similar lava also occurs in the Black Hills, on the west side of the Verde Valley opposite the Black Mesa. East of the

[1] For analyses of the lava and clay, see p. 150.

[2] Personal communication.

[3] Robinson, H. H., The Tertiary peneplain of the Plateau district and adjacent country in Arizona and New Mexico: Am. Jour. Sci., 4th ser., vol. 24, 1907, pp. 109-129.

San Franciscan region the nearest area is in the Rabbit Ear Mountains, 80 miles distant. This is an isolated field which once covered between 500 and 1,000 square miles but is now eroded into many mesas and buttes, some of the latter being volcanic necks. Red Butte, north of the San Franciscan region, as well as Mount Trumbull and the other higher mesas near it, north of the Grand Canyon, are capped by the older basalt. Dutton's description [1] of the basalts of the Uinkaret Plateau may be correctly applied to large areas in the southern part of the Plateau country. At all these places the basalt rests on a peneplain. Although these localities can not be exactly correlated, it is believed that all of them, with the possible exception of a single area in the Little Colorado Valley, were peneplained during the same cycle of erosion. It thus seems probable that the basalt resting on a peneplain at the localities cited and even over a wider area in the southern plateau country was erupted during a period that essentially coincided with the first general period of eruption in the San Franciscan volcanic field.

SECOND GENERAL PERIOD OF ERUPTION.

During the second period of volcanism six isolated cones of large size and a somewhat greater number of small cones were formed by the eruption of lavas ranging in composition from andesites to rhyolites. These cones are individually described under the heading "Volcanoes of the second period." Several laccolithic and semilaccolithic masses are also assigned to this period, as they are directly correlated with the eruptions by the upturned lavas on their flanks. Of these masses Marble Hill is a true laccolith, but Elden Mountain and probably Slate Mountain present a unique combination of volcanic extrusion and laccolithic intrusion in the same geologic unit. They are separately described under the heading "Laccoliths of the second period."

VOLCANOES OF THE SECOND PERIOD.

SAN FRANCISCO MOUNTAIN.

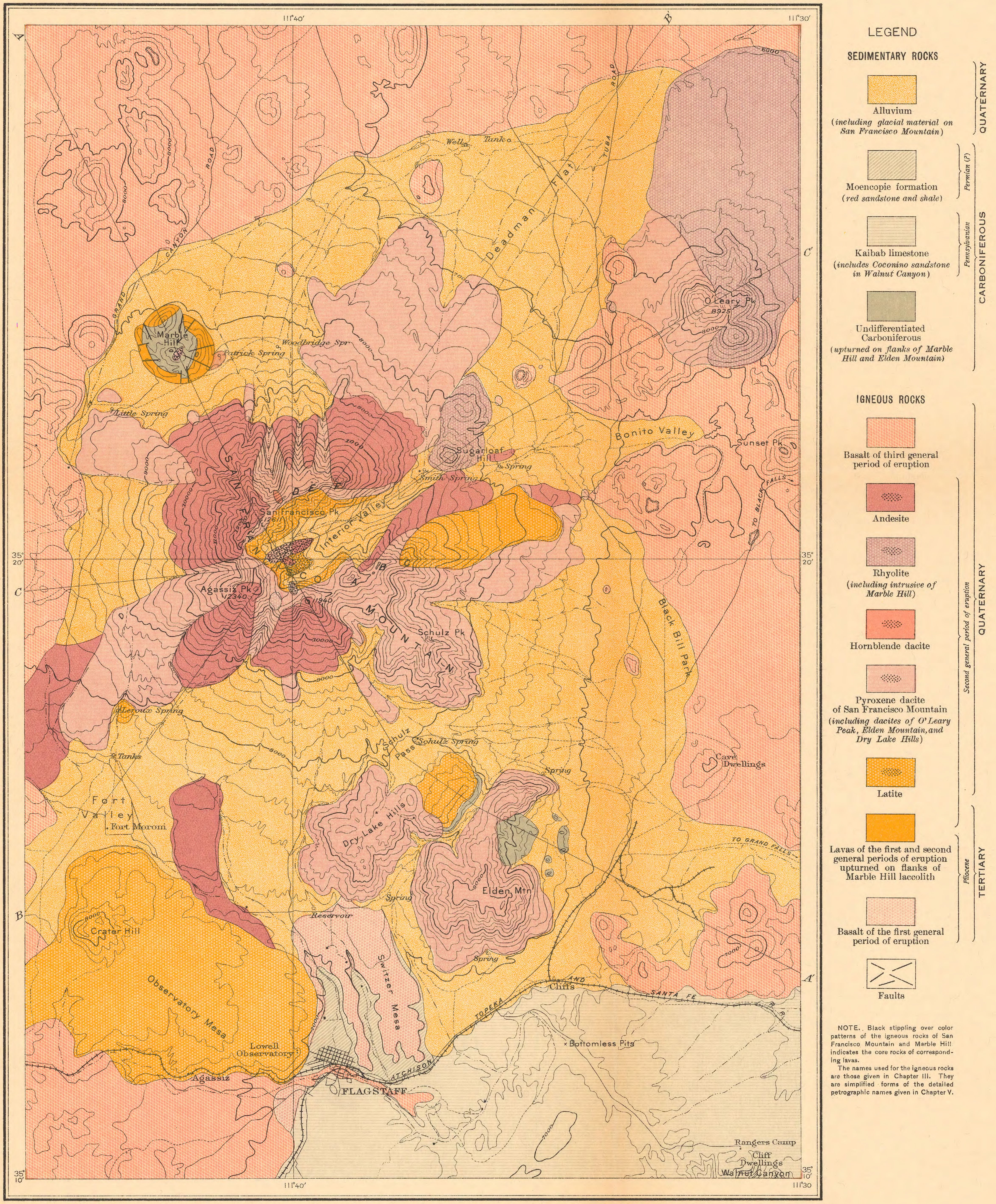
TOPOGRAPHY.

The dominant feature of the region is San Francisco Mountain (see Pl. V), which rises in San Francisco Peak to a height of 12,611 feet above sea level, or about 5,000 feet above the surface of the plateau. It is by far the most prominent landmark in this portion of the Colorado Plateau and is, indeed, the highest elevation in the Southwestern States.

The outline of the mountain, seen from any point sufficiently distant to mask the topographic details, conveys a strong impression of the volcanic origin of the mass. The slightly concave slopes rise uniformly on either side and the rather irregular crest line indicates that the cone has been somewhat eroded. On closer approach the outlying cones and lavas confirm the impression received at a distance. The slopes still retain their regular outline but are scored by ravines and on the east and southeast are interrupted by secondary cones. The crest line is resolved into six principal and several minor peaks, all over 11,000 feet in elevation, separated by divides of but little lower altitude. Three of these peaks have received names. On the north is the highest, San Francisco Peak; on the south are Agassiz and Fremont peaks, with elevations of 12,340 and 11,940 feet, respectively. In the view from Flagstaff, at the southern base of the mountain, where the eastern slope is hidden by intervening hills, the long, gently concave western slope at once reveals the character of the mountain. Likewise in views from the east, which exhibit the maximum amount of erosion, there is no difficulty in perceiving the nature of the mass; in fact, when the details of the geology are known, this viewpoint has a greater interest than any other, as will appear later.

The inclination of the outer slopes of the mountain about the rim, which closely agrees with the dip of the lava flows, is between 20° and 22° and decreases uniformly toward the foot slopes. Thus the surface of the flows at the northeast base of the cone has an inclination

[1] Op. cit., pp. 104-112.



GENERAL GEOLOGIC MAP OF SAN FRANCISCO MOUNTAIN AND VICINITY, ARIZONA

R. B. Marshall, Chief Geographer
T. G. Gerdine, Geographer in charge
Topography by Pearson Chapman, T. F. Slaughter, and J. W. Muller
Control by H. L. Baldwin, Jr., J. T. Stewart, and T. A. Green
Surveyed in 1907 and 1908

Scale $\frac{1}{96000}$

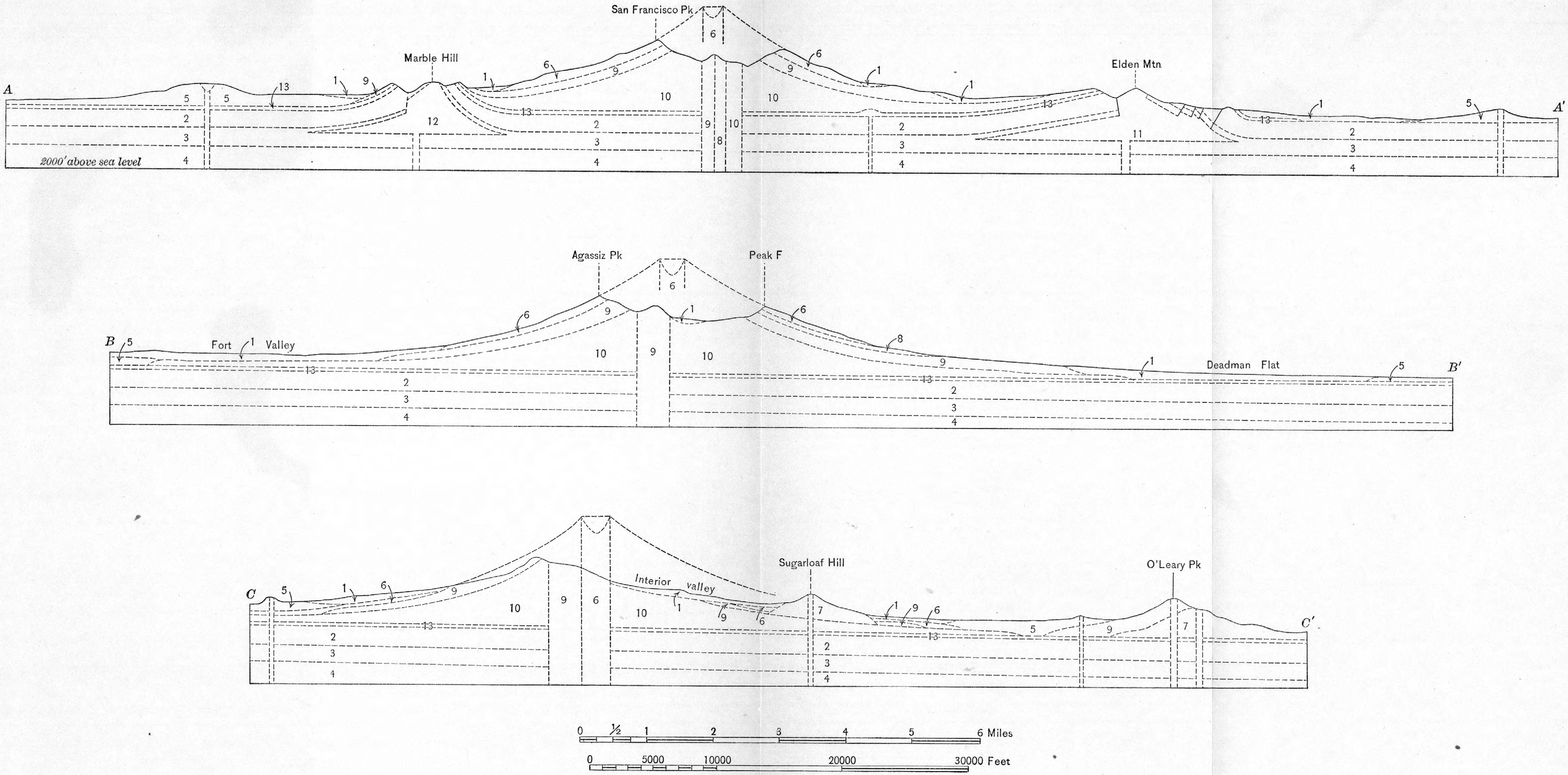
1 0 1 2 3 4 5 Miles

Contour interval 200 feet

Datum is mean sea level

1913

Geology by H. H. Robinson
Surveyed in 1903



GEOLOGIC CROSS SECTIONS OF SAN FRANCISCO MOUNTAIN AND VICINITY.

1, Alluvium (Quaternary); 2, Pennsylvanian formations (undivided); 3, Mississippian (including some Pennsylvanian); 4, pre-Carboniferous (undivided); 5, basalt (third general period of eruption), 6, andesite (second general period of eruption); 7, rhyolite (second general period of eruption); 8, hornblende dacite (second general period of eruption); 9, pyroxene dacite (second general period of eruption); 10, latite dacite (second general period of eruption); 11, dacite of Elden Mountain (intrusive portion); 12, granite porphyry of Marble Hill; 13, basalt (first general period of eruption).

of 5°, whereas that of the flow east of Fort Valley is but 2°. The maximum observed slope, 22°, is on the average about a mile, measured along the slope, below the former summit of the cone. (See cross sections, Pl. VI.) A slope of 33° at the original summit is indicated, however, by the restored outline. For comparison with San Francisco Mountain in respect to form, Mount Shasta, in California, has been chosen, and the outlines of the two volcanoes are shown in figure 4. In this figure the cross section of Shasta is drawn in an east-west direction through the summit and Shastina, the outline of the main cone being indicated by the dotted line; the section of San Francsico Mountain is drawn along the line B–B′ of Plate V. The platforms on which the cones rest have been brought into coincidence so that the relative size of the two volcanoes is correctly represented. The resemblance of the two is very close and perhaps the more striking because the restoration of San Francisco Mountain was made without reference to any other volcano. It would seem that so close a similarity in form could result only from similar factors of development, which is further indicated by the general resemblance of the several lavas of the two volcanoes and their common mode of eruption.

The upper slopes of the mountain down to elevations of 9,000 or 10,000 feet are scored by numerous ravines which are sharply incised and terminate abruptly at the waste fans that have been built out from their mouths. The most striking erosional feature of the mountain is the large interior valley which heads under San Francisco and Agassiz peaks and runs northeastward for 3 miles, completely breaching the eastern wall of the volcano down to the level of 8,500 feet. The head of the valley is divided into two arms by a prominent ridge which

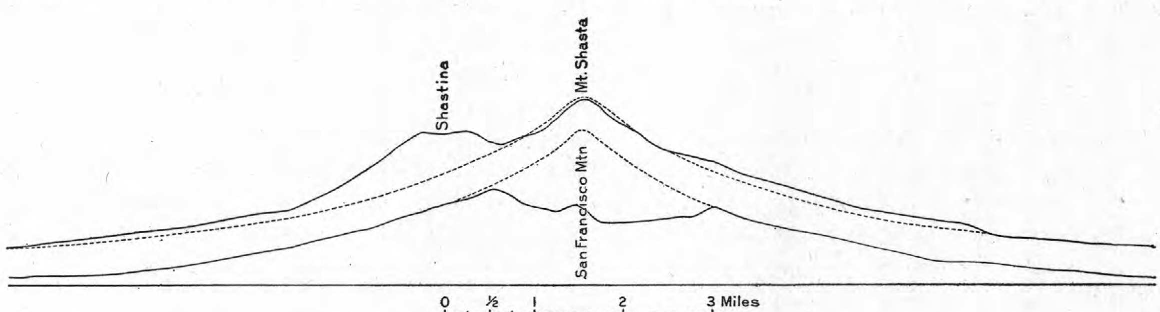


FIGURE 4.—Profiles of Mount Shasta and San Francisco Mountain.

starts at the western crest of the cone, nearly midway between the two peaks above mentioned, runs eastward at an average elevation of 11,250 feet for three-quarters of a mile, and thence drops sharply to the valley floor. The eastern extension of the valley was obstructed by Sugarloaf Hill, at the foot of which it turns abruptly northward and is continued in a box canyon for 2 miles to Deadman Flat. This valley gives to the crest of the mountain the shape of a horseshoe, the open end being toward the northeast.

The distance separating the ravines on the north, south, and west outer slopes of the cone, where they have developed on lava of the same stage of eruption, ranges between 0.5 and 0.7 mile. Such uniform spacing seems rather to represent the spontaneous adjustment of drainage to slope than to be the result of chance location of drainage lines along depressions. There are, however, several ravines whose position has been fixed by contacts between lavas of different stages of eruption. Such is the origin of the ravines on the east side of the mountain and of those on the southwest side under Agassiz Peak. The position of the interior valley appears to have been determined, at least in part, by the fact that the northeast slope is more susceptible to erosive forces than the others. It is the shadiest side of the mountain, consequently it has a greater accumulation of snow during the winter and a larger run-off during the spring melting. It also probably receives the greater part of the rain in the summer season. The conditions that have fixed the line of maximum erosion on the northeast slope of San Francisco Mountain are not local, for Mount Taylor in New Mexico exhibits a similar arrangement of valleys, and Kendrick and Sitgreaves peaks do so to a less extent.

The outer slopes above timber line, approximately 11,500 feet, are largely covered with angular blocks of lava which in this situation indicate pronounced frost action. The stripping by this process is most evident on the outer slope of San Francisco Peak and to a less extent on Agassiz Peak; it is greater where the surfaces rather than the edges of lava flows are exposed. Landslides are not uncomon in the upper (western) part of the interior valley, where the surrounding walls, 1,500 feet high, are composed largely of ash and breccia. They are not present in the lower part, where the walls have decreased in height and are composed of lava flows.

The material eroded from the upper part of the mountain and brought down the ravines has been spread over the lower slopes in a series of coalescing fans. These alluvial fans, as in most other mountains in the Southwest, constitute a prominent feature in the topography of the volcano, their long, gentle slopes and comparatively smooth surfaces contrasting sharply with the steep and rugged slopes above them (Pl. VII, *B*). The larger fans on the south and west sides of the mountain almost entirely cover the original slopes up to about 10,000 feet, whereas on the north and east sides the upper limit of fans does not exceed 8,000 feet. They encircle the base of the cone for two-thirds of its circumference, and the large area covered by them may be seen on the geologic map (Pl. V). In contrast to the outer slopes, the floor of the interior valley between 9,200 and 10,500 feet is composed of morainic material deposited by a former glacier, and an outwash plain extends from the terminal moraine to the east end of the valley. The alluvial fans and glacial material are now being dissected and the eroded waste is being redeposited on lower and flatter slopes. An estimate of the amount of alluvial material on the slopes and about the base of the cone shows that it constitutes 75 per cent of the total quantity of material eroded from the mountain. This clearly indicates that on the whole the rate of disintegration has exceeded that of transportation.

The amount of material removed from the slopes of the cone has not been large, and except along the ravines and above timber line the outer slopes may be considered as little altered by erosion. It is true that they are somewhat weathered and covered with a thin mantle of soil, which is prevented from washing by a heavy growth of spruce and fir, but on the whole the area of unconsumed interravine slopes is extensive. This condition shows that the mountain is in a youthful stage of dissection.

GENERAL STRUCTURE OF CONE.

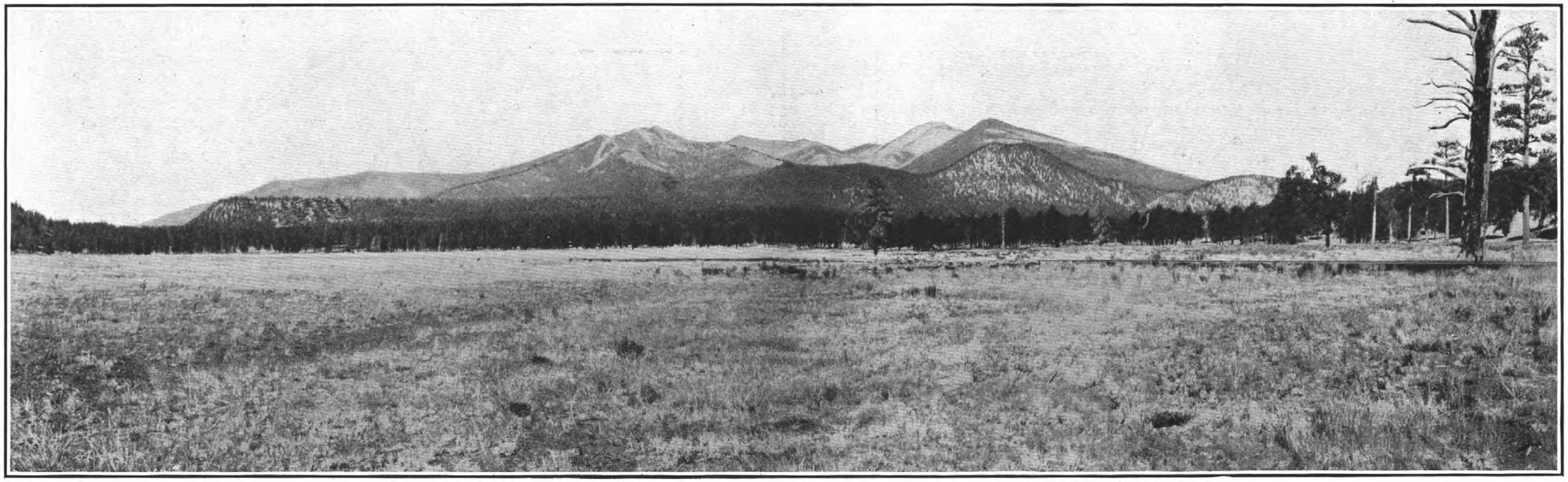
The structure of the volcano may be clearly made out from the position of the lavas and breccias, which have a maximum exposure of 2,000 feet, in the walls of the interior valley, and also by the lava flows on the outer slopes of the cone. These beds without exception dip away on all sides from a central mass of igneous rock which forms the sharp ridge at the head of the interior valley. This ridge, therefore, must represent the neck of the volcano, and it gives the restored original outline of the cone (fig. 5 and cross sections in Pl. VI) a high degree of accuracy. It happens that in the view of the mountain from the east (Pl. VII, *A*) the core ridge can be seen at the head of the interior valley, so that the original form of the volcano may be readily visualized in the field.

ERUPTIVE HISTORY.

VARIETIES OF LAVA.

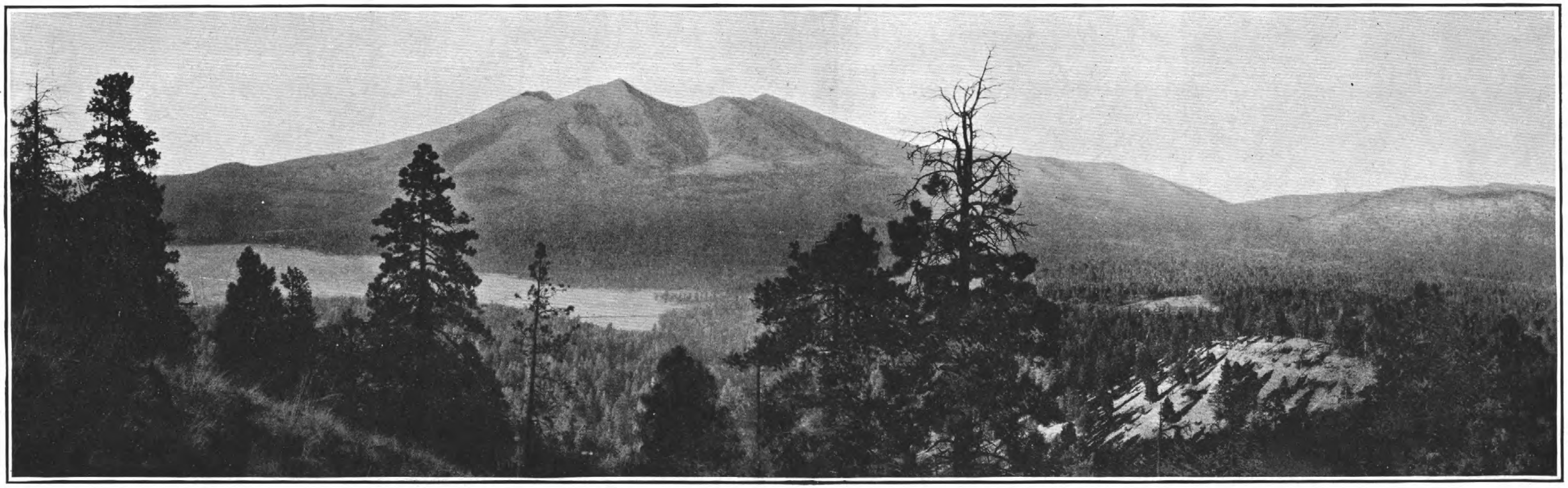
San Francisco Mountain is formed by lavas and breccias belonging to five distinct stages of eruption. It is composite both with respect to the character of its materials and the varieties of its lavas. The main vents from which the lavas escaped, with one exception, are all located close together within the area occupied by the core ridge at the head of the interior valley, and for this reason the volcano has a very symmetrical outline. (See fig. 5.)

Partial analyses of the lavas are given on the next page.



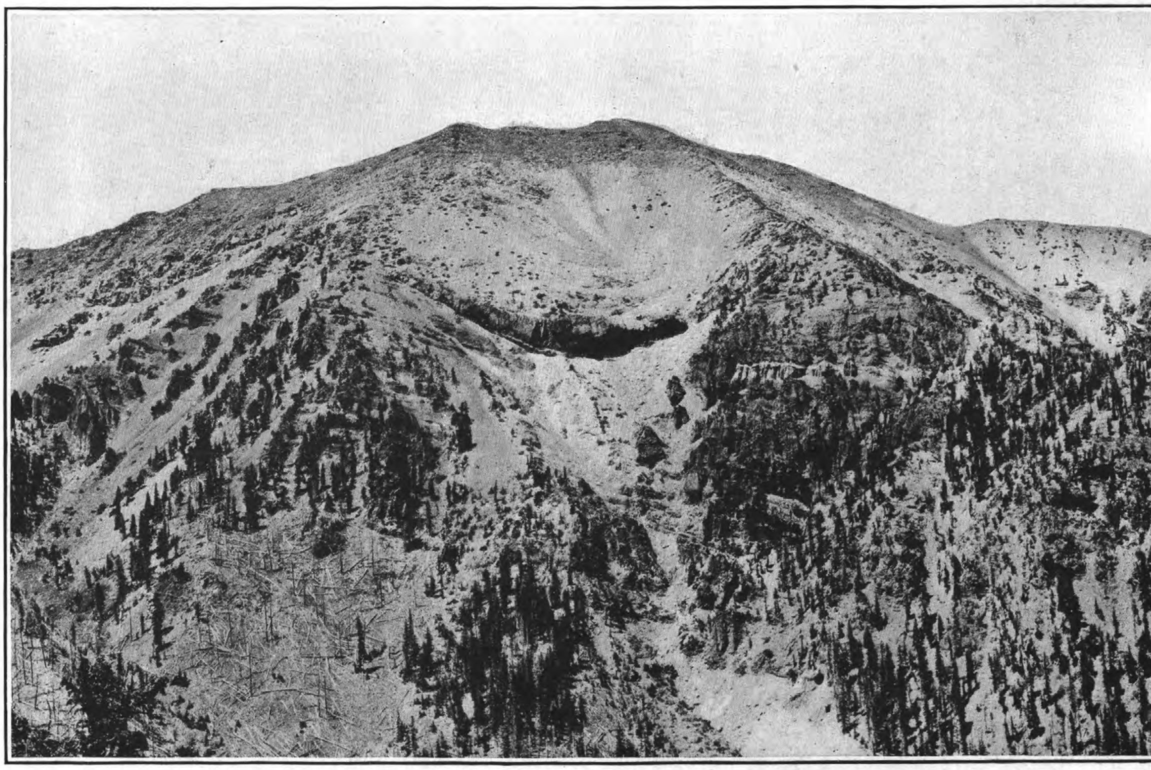
A. SAN FRANCISCO MOUNTAIN FROM VALLEY BONITO ON THE EAST.

Looking up the interior valley at the head of which rises the core of the volcano. The light-colored cone in the middle distance at the right is Sugarloaf Hill. That in the distance at the left is Schulz Peak.



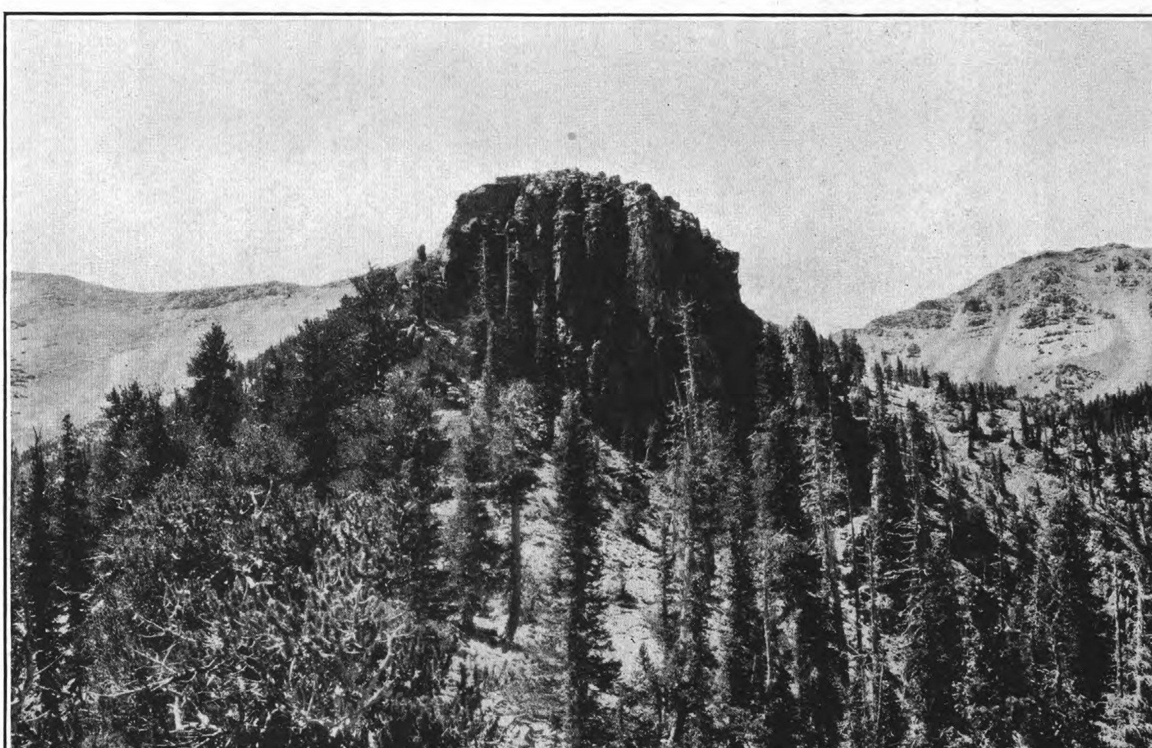
B. SAN FRANCISCO MOUNTAIN FROM CRATER HILL ON THE SOUTH.

Agassiz Peak in the center, San Francisco Peak on the left, Fremont Peak on the right. Schulz Peak just to right of dead pine. Treeless area at foot of Agassiz Peak is Fort Valley. Shows upper slopes cut by youthful ravines; lower slopes heavily mantled with alluvium.



A. INNER (SOUTHEAST) SLOPE OF SAN FRANCISCO PEAK, FROM CORE RIDGE.

Lower slope is composed of andesitic lavas and breccias of the first stage of activity. Middle slope, dacite of second stage; basal flow, marked by cliff, escaped through a depression in older rim. Upper slope and summit, darker colored than the dacite, is augite andesite of fifth stage. Light-colored V-shaped area at right is the dacite of the third stage of activity.



B. NECK OF AUGITE ANDESITE OF FIFTH STAGE OF ACTIVITY.

Showing rude vertical columnar structure.

Partial analyses of lavas from San Francisco Mountain.

[Numbers indicate order of eruption.]

	1. Latite.	2. Pyroxene dacite.	3. Hornblende dacite.	4. Rhyolite.	5. Andesite.
SiO_2	59.8	64.6	66.5	74.0	57.6
Al_2O_3	17.0	16.6	16.6	13.1	17.1
Fe_2O_3	6.0	2.6	2.2	1.4	3.1
FeO	.9	2.4	2.6	1.2	5.2
MgO	2.1	.9	.9	Tr.	2.8
CaO	4.1	3.1	2.8	.1	5.6
Na_2O	4.5	5.1	4.6	5.8	4.2
K_2O	2.9	3.4	3.4	4.3	2.1
TiO_2	1.1	.8	.6	.1	1.6
	98.4	99.5	100.2	100.0	99.3

The lavas, as shown by the analyses, exhibit a considerable variety in composition. The two dacites have the same chemical composition and nearly similar mineral composition but belong to different stages of eruption. The latite and andesite do not differ greatly in chemical composition, although the andesite is slightly the more basic. They are, however, distinctly separated mineralogically and texturally. The eruptions began with a lava of intermediate composition, the succeeding lavas through the rhyolite were increasingly acidic, and the last lava erupted was more basic than the first.

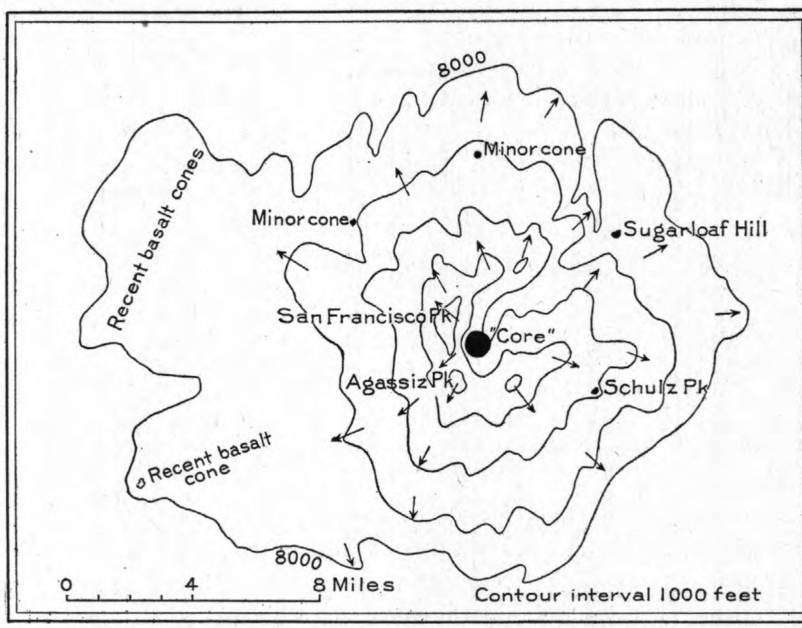


FIGURE 5.—Sketch showing location of main vent and directions of flows, San Francisco Mountain.

FIRST STAGE OF ERUPTION.

The greatest thickness of beds belonging to the first stage is exposed on the inner (southeast) slope of San Francisco Peak. The exposure consists of twenty beds of lava, breccia, and tuff, with a thickness of nearly 1,000 feet. Seven of these beds are lava flows with a total thickness of 335 feet; the remaining thirteen are made up of fragmental material and measure 715 feet. The lava is thus about half as thick as the fragmental material, but if allowance were made for the porosity of the latter this proportion would be increased. There is a regular alternation, extending through fifteen beds, from compact lava to breccia or ash, but whether this succession in a general way holds for the entire stage of eruption can not be stated. This exposure forms only the upper one-fifth of the total thickness of beds of the first stage, so that some 4,000 feet of material belonging to the early eruptions is entirely hidden from view. (See cross section A–A′, Pl. VI.)

It is thus possible that the earliest eruptions of San Francisco Mountain may have been of a lava different in composition from any observed. A cone between 2,000 and 3,000 feet high could be buried beneath the lowest exposures in the interior valley. It is not probable, however, that the basal flows are of different composition from those exposed in San Francisco Peak. This is indicated by the fact that the only lavas found at the other large cones of the region are those actually exposed at San Francisco Mountain, although the sequences are not of the same order and completeness. That this inference is correct will become clear in the following pages and need not be discussed here.

Material which belongs to the first stage and whose position shows that it came from the main vent outcrops only here and there about the foot of the mountain. As would be expected, it has largely been covered by later lavas. The most extensive exposure is on the north flank of Elden Mountain and consists predominantly of breccia and ash. The second largest outcrop is compact lava and lies just east of Leroux Spring. Lava also occurs on the flank of Marble Hill.

In addition to the exposures above noted there is a large mass of latite on the east slope of the mountain which closely resembles the lava found elsewhere. (See Pl. V.) It must have been erupted, however, from a secondary vent situated on the lower slope of the main cone. As may be seen from the cross section through this locality (fig. 6), the restored slope of the main cone lies 2,000 feet below the highest exposure of this mass of lava. The surface slope of the flow at its lower end is nearly flat, whereas the front and side slopes are steep. The north and south sides of the mass are slightly higher than the center; they most probably represent the rapidly cooled edges of the flow. These features and the relation of the later lavas show that the present boundary of this latite mass coincides closely with the original one.

The position of the main vent of the first stage is determined in part by a confused mass of breccia and lava which lies south of the east end of the core ridge at the head of the interior valley. The location of the entire vent can not be fixed on account of the absence of exposures. It is probable that the orifice extended farther north and that this part of it is now occupied by the core rocks of the later stages of eruption. So far as can be told from the known exposures of latite, the eruptions came predominantly from this central vent.

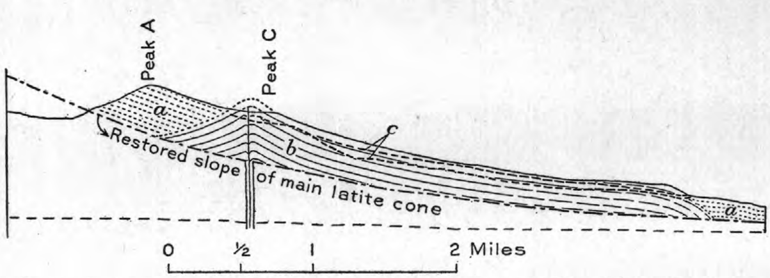


FIGURE 6.—Section through Peak A and east slope, San Francisco Mountain. *a*, Dacite; *b*, latite; *c*, elevation of later surrounding lavas.

The thinness of the flows in the San Francisco Peak section and the flat slopes of those at the base of the mountain make it probable that the lavas of this stage did not extend beyond the foot slopes of the volcano. The heavier fragmental material and some ash, about as coarse as ordinary sand, fell on the slopes. From the explosive character of many of the outbreaks it would seem that a considerable quantity of finer ash and dust must have been distributed over a wider area, although no such deposits were observed.

The height of the cone formed by the eruptions of the first stage was 7,400 feet, as determined from the restored outline on the cross sections, and its volume was 21 cubic miles. The exposures on the inner slope of San Francisco Peak and elsewhere show that during the later part of the stage, and presumably during the entire stage, the volcano was very active. The number of separate outbreaks is estimated to have been between 100 and 200, of which two-thirds were explosive and the remainder quiet. This initial stage of activity of San Francisco Mountain may be considered, therefore, as consisting of alternating explosive and quiet phases, the former predominating.

SECOND STAGE OF ERUPTION.

Pyroxene dacite erupted during the second stage of activity occurs in the upper part of the walls of the interior valley at its west end and in their lower part at the east end. At all points it rests directly on the latite of the preceding stage. It outcrops on the divides between the principal peaks and at the summit of Peak A. This dacite is also the surface rock over large areas on the northeast, northwest, southeast, and southwest sides of the cone. (See Pl. V.) At every locality the lava occurs in the form of rather thick massive flows; fragmental material was nowhere observed.

At several points in the walls of the interior valley, of which the most prominent is on the inner slope of San Francisco Peak (Pl. VIII, *A*), the dacite fills depressions in the latite. The form of these depressions shows that they are ravines eroded on the slope of the latite cone after it became extinct. Evidently therefore an interval of quiescence ensued between the close of the first and the beginning of the second stage of activity. It is difficult, however, to form a definite idea of the length of this period. These ravines are not as large as the present ones on the outer slopes of the cone. They are also cut, for the most part, in unconsolidated breccia and ash, whereas the present ravines are in lava. It would appear (assuming constant erosive forces) that the interval between the first and second stages was very much shorter than the time which has elapsed since the cone finally became extinct.

A mass of dacite in the core ridge marks, in part at least, the position of the main vent of the second stage. The western contact with the breccia of the preceding stage is exposed at an elevation of 11,750 feet a quarter of a mile east of the San Francisco-Agassiz saddle. The contacts elsewhere are with younger rocks. The direction of several dacite dikes in the north wall of the interior valley indicates that the vent may have extended to the east end of the core ridge, where later rocks are now present. The size of the vent is approximately 1,000 by 2,000 feet or more, depending on the position of the eastern boundary. This is at a horizon 1,800 feet below the restored summit of the dacite cone. The structure of the core rock is diverse. In the western part of the vent the rock is compact and has a pronounced platy structure; it also has a very irregular vertical jointing system, but it does not develop columns.

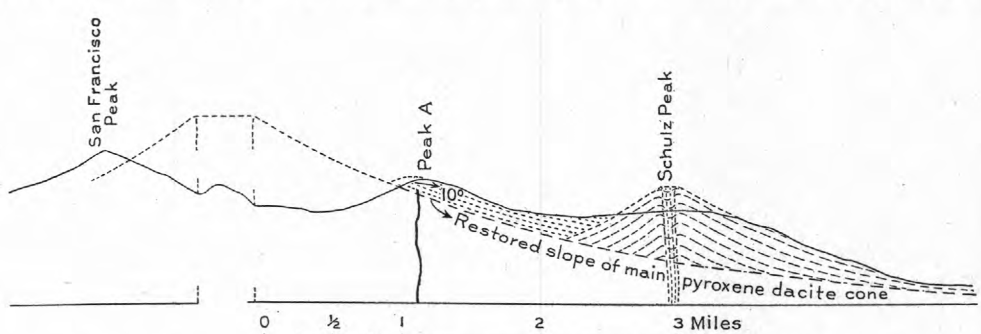


FIGURE 7.—Section through San Francisco Peak, Peak A, and Schulz Peak, San Francisco Mountain.

Toward the east end it is more massive and tends to weather in spheroidal forms. The intermediate space is occupied by an agglomerate whose matrix is filled with large and small fragments of decomposed lava. The restoration of the cone shows that practically all the lava exposed in the walls of the interior valley, which represents by far the greater part erupted, came from this central vent.

The position of the dacite of the second stage on the outer slopes of the mountain indicates that most if not all of it was erupted from lateral vents. This lava is, of course, younger than that which is exposed in the walls of the interior valley and which came from the central orifice. It appears, therefore, that the eruptions during the later part of the second stage came from small lateral vents, whereas during the earlier and longer part they came from a single central orifice.

Schulz Peak, on the southeast slope of the mountain, is the largest of these secondary dacite cones and its relation to the main cone is shown by the section through the locality (fig. 7). According to this restoration the peak had an original height of 2,800 feet and has been lowered by erosion some 900 feet. These figures are based on the assumption that the cone was distinctly conical rather than dome-shaped. The outer slopes are strongly scored by ravines and show little lava in place. The cone appears, on the whole, more dissected than San Francisco Mountain, perhaps because of its somewhat greater age and the less firm texture of the lava. An agglomerate, weathered in pinnacles, outcrops in one of the larger ravines on the south side facing Schulz Spring and locates with some precision the vent of the cone.

The large mass of dacite at the northeast base of the mountain clearly came from the small parasitic cone situated 1¾ miles north of Peak F at an elevation of 9,250 feet. The dacite capping Peak A also appears to have been erupted from a small independent vent. The lava has a dip of but 10°, compared with dips of 20° to 30° in the dacite at other localities of equal elevation, and the section through this locality (fig. 7) shows that it lies 600 feet above the restored slope of the main dacite cone. Of like origin are the flows on the southwest side of the mountain, and the vent from which they came is located on the outer slope below Agassiz Peak, at an elevation of 11,600 feet. These flows extend directly down the slope to an elevation of 9,000 feet, where they turn to the south. Their southernmost limit is on the north side of Fort Valley, at 7,500 feet. The ends of two other dacite flows are situated north of Leroux Spring at elevations of 8,000 and 8,500 feet.

The dacite of the second stage is found at greater distances from the center of the cone than any of the other lavas because of the eruptions from the lateral vents. The surface slope of the flows at the northeast base of the mountain is rather flat—about 5°—whereas the side and front slopes are steep. At several localities on the cone, however, flows terminate on slopes as steep as 15°, and elsewhere, as at Elden Mountain and the Dry Lake Hills, dacite of the same composition forms craterless, dome-shaped cones characteristic of viscous eruptions. These facts and the generally slightly eroded condition of the flows lead to the conclusion that the dacite never extended much beyond its present limits. If lava flows only are considered, it is evident that San Francisco Mountain attained its maximum basal area during this second stage of activity.

The dacite from both the central and the lateral vents forms thick flows of massive appearance and tends to weather in spheroidal forms. A characteristic feature of the lava in San Francisco Mountain, as well as at several other localities, is the presence of numerous small inclusions of a dark-colored igneous rock. These inclusions are segregation products more basic in composition than the dacite and they invariably contain hornblende, whether or not this is the characteristic dark mineral of the lava.

The second stage of eruption appears to be divisible into two substages. During the first and longer one there were many eruptions of lava from a single central vent. They somewhat shattered the older latite cone, as shown by dikes now exposed in the walls of the interior valley, which radiate from the central core. A single dike in the upturned sedimentary rocks on the flanks of the Marble Hill laccolith, at the northwest foot of the mountain, suggests that the fissuring was not confined to the immediate vicinity of the main conduit. The lava of the first eruptions overflowed the rim of the latite cone through several depressions and when these were filled up it overran the older rim throughout its circumference. Restorations show that the volcano was built up by these eruptions to a height of 8,200 feet, or 800 feet higher than the latite cone of the preceding stage. Its volume was increased to 32 cubic miles by the addition of 11 cubic miles of material, wholly in the form of lava.

During the later part of the second stage the eruptions came from small lateral vents instead of from the central orifice. There were at least six such vents, all situated on the outer slopes of the cone. The eruptions from these vents were the last eruptions of the second stage, as the lava now forms the slopes of the mountain. They added nothing to the height of the cone, but increased its volume to 34 cubic miles by the addition of 2 cubic miles of material. It is probable that the mountain attained its maximum basal area at this time as the result of these eruptions of dacite from lateral vents. As during the first part of the stage, only lava in heavy flows was erupted. The entire stage, therefore, was characterized by quiet but powerful outwellings of lava in large volume.

THIRD STAGE OF ERUPTION.

The hornblende dacite of the third stage was observed only at a few localities in the upper part of the cone. It is probable that this lava occurs in small amount, estimated at half a cubic mile. The principal outcrop is just west of Peak D. It consists of a sheetlike mass of light-colored lava, which cuts across and has slightly metamorphosed the dacite of the second stage of eruption and possibly the latite of the first stage. It may be recognized in Plate VIII, *A*, as the light-colored V-shaped wedge (the lower part is talus) at the crest line of the mountain on the extreme right of the picture. On account of the eroded condition of the mass it is difficult to determine its relation to the older dacite. The lava may lie in what was a ravine on the slope of the pyroxene dacite cone. A second locality is at the west base of Peak F, at an elevation of 11,500 feet, where the exposure consists of a thin bed of pumice. No lava of the third stage was definitely recognized about the foot slopes of the mountain; nearly all the dacite so situated clearly belongs to the preceding stage. It does not seem probable, in view of the meager outcrops in the upper part of the cone, that any flows of hornblende dacite reached the foot of the mountain.

A confused mass of rock on the south-central side of the core ridge marks the position of the vent of the third stage. The rock is somewhat more compact than the effusive type; it is also more coarsely crystallized and contains a smaller proportion of phenocrysts. An irregular contact with the older dacite core occurs about halfway up the south slope of the ridge, and on the east the rock is decidedly bleached and altered along the contact with the later andesite core rock. On the south the rock is in contact with an agglomerate of the first stage. The size of the core is roughly 500 by 1,000 feet, but within this area are several masses of agglomerate which may not belong to this stage.

Although the evidence is slight, it would appear that the eruptions of the third stage were in part quiet, in part explosive, and of small volume. They were not as vigorous as those of the second stage, as shown by the smaller number of dikes and their closer confinement to the vicinity of the vent. The size of the conduit seems quite disproportionate to the amount of lava apparently erupted. This suggests that the eruptive forces, although initially strong enough to open the vent, were too weak to expel lava from it.

The field evidence is too indefinite for estimating the interval between the second and third stages of eruption. The lavas of the two stages have the same chemical composition and only minor mineralogic differences. Their similarity points to a very brief interval between their eruption, as compared with the intervals between the other stages. The conclusion rests on the assumption that differentiation of the magma proceeded at a uniform rate, so that there is a direct relation between its extent and time. This is not true, however, for the entire sequence of lavas. The interval between the fourth and fifth stages, during which the maximum change in the composition of the lavas occurred, appears to have been no longer than those between the first and second or the second and fourth stages.

FOURTH STAGE OF ERUPTION.

The only outcrop of rhyolite in San Francisco Mountain is in the saddle between Agassiz and Fremont peaks. The lava occurs in thin flows composed mostly of light-reddish banded spherulitic varieties and a minor amount of lustrous black glass. It is evident that the original volume of the lava must have been small; it is estimated at half a cubic mile. In views from the south the mass may be distinguished from the underlying lavas by its lighter color.

The core rock of this stage is found on the inner (northwest) slope of Fremont Peak at an elevation of 11,000 feet. Although none is in place, there is no doubt that it marks the position of the rhyolite vent. The rock is bluish-gray in color and thoroughly compact. Of the five core rocks it is the only one that may be seen megascopically to have a holocrystalline, or, to speak more strictly, a cryptocrystalline texture. The restoration of the volcano shows that the mouth of this orifice was originally on the outer slope, and the relation of the rhyolite to the dacite in the Agassiz-Fremont saddle indicates that the side of the cone was somewhat disrupted in the opening of the vent.

The rhyolite eruptions are shown by field evidence to have occurred only between the second and fifth stages of activity. However, it is considered practically certain that the hornblende dacite was erupted immediately after the pyroxene dacite, so that the rhyolite must be assigned to the fourth stage of activity.

FIFTH STAGE OF ERUPTION.

The andesite of the fifth and last stage of eruption at San Francisco Mountain caps the summits of all the principal peaks and is the surface rock on the north and in part on the south, east, and west sides of the cone. At most localities it rests on the pyroxene dacite of the second stage, as is illustrated by Plate VIII, *A*, where the dark-colored lava at the summit of the mountain is andesite and that below is dacite. In Peak F, however, it overlies the hornblende dacite pumice of the third stage, and the restoration of the cone shows that it bears the same relation to the rhyolite in the Agassiz-Fremont saddle. Eroded remnants of the andesite, very fine grained and rather scoriaceous, occur on the northeast (inner) slope of Peak A about 250 feet below the summit. From this vicinity to the base of the cone on the east side the andesite is in contact with the latite of the first stage, which came from a secondary vent. On the east side, also, the andesite is seen to overlie the rhyolite of Sugarloaf Hill.

On the south a single stream of andesite extends 7½ miles from the center (crater) of the cone, which is a greater distance than is covered by any other lava, so far as observable. The flows of this stage probably extend to or beyond the base of the mountain on the north, east, and west sides, to judge from the thickness of the outcrops in upper slopes, although this can not be seen on account of the covering of later lava and alluvium. On the northeast side, however, the flows terminate on the middle slopes at a distance of 3 miles from the center of the cone.

The mass of andesite at the east end of the core ridge (Pl. VIII, *B*) marks the position of the orifice through which all the lava was erupted. On the west it abuts against older core rocks, and on the other sides, although the contact is covered by glacial drift, it would appear to be in juxtaposition with the latite (either as lava or core rock) of the first stage. The length of the plug east and west is approximately 1,500 feet and its width 1,000 feet. The rock exposed in the upper part of the core, now about 3,500 feet below the original summit of the cone of this stage, is dark gray in color, is uniformly compact, and has an aphanitic texture. Under the microscope it is seen to be more coarsely crystalline than the rhyolite core rock, which megascopically would be considered holocrystalline. Megascopically, therefore, the more coarsely crystalline andesite porphyry is defined as having an aphanitic texture and the less coarsely crystalline granite porphyry as having a holocrystalline texture. This anomaly in definition is due simply to the difference in the color of the two rocks and is but one of many encountered in the classification of rocks by their megascopic characters.

Andesite dikes, so far as observed, are confined to the vicinity of the conduit through which the lava was erupted. One occurs in the core rock itself, indicating slight disturbances in the vent after the main eruptions had ceased. The presence of dikes only near the vent suggests that the outbreaks were not violent.

The interval between the fourth and fifth stages appears to have been short. In fact, the regularity of the extensive contact between the pyroxene dacite and the andesite would seem to indicate that the interval between the second and fifth stages was no longer, perhaps, than that between the first and second stages. The bed of hornblende dacite pumice under Peak F may be considered as pointing to a short interval between the third and fifth stages. Pieces of the pumice an inch in diameter float in water about five minutes before sinking. The presence of such light material on a slope of 20° suggests a short period of time or the feeble action of erosive forces. In the absence, however, of any knowledge as to the relative erodibility of the different lavas, these estimates should not be given much weight.

The fifth stage of eruption was characterized, then, by quiet but rather vigorous outwellings of andesite unaccompanied by explosive phases, as shown by the absence of any fragmental material. The lava was erupted in sufficient volume to overflow the entire circumference of the older rim of the volcano. However, the flows were not thick enough to bury the masses of pyroxene dacite and latite that escaped from lateral vents and rose above the slopes of the cone built up by the eruptions from the central vents. As shown by the restored outlines, the cone reached its maximum height of 8,800 feet, or 600 feet above the summit of the dacite cone, at the close of this stage and its volume was increased to 38 cubic miles by the addition of 3 cubic miles of lava.

VOLUME OF THE CONE AND OF THE INDIVIDUAL LAVAS.

The volcano has been so slightly eroded since it became extinct that it is possible to restore the original outlines with considerable accuracy (see cross sections, Pl. VI), and from them to calculate the volume. The volume obtained is the average of the volumes of the three cones of revolution generated by the restored outlines of the cross sections. The results are of course not exact, but the conditions of the problem do not appear to call for greater accuracy. Considerable differences will be noted in volumes of the cones generated by the three sections, which are due to the somewhat unsymmetrical form of the cone. These differences, however, will not affect the average result unless the cross sections have been inappropriately chosen.

The calculations of the volume of the main cone and of the lava of each stage of eruption are as follows:

Total volume of main cone of San Francisco Mountain.

Cone generated by—	Cubic miles.
Section A–A′	33.4
Section B–B′	36.8
Section C–C′	38.9
Average nearest integer	36.0

Volume of latite cone (first stage) of San Francisco Mountain.

Cone generated by—	Cubic miles.
Section A–A′	17.8
Section B–B′	20.7
Section C–C′	24.5
Average	21.0

Volume of cone of San Francisco Mountain at close of second stage.

Cone generated by—	Cubic miles.
Section A–A′	29.9
Section B–B′	33.6
Section C–C′	36.3
Average	33.0

The last figure includes the volumes of the hornblende dacite and rhyolite stages, estimated at 1 cubic mile. Corrected for this, the volume would be 32 cubic miles.

The volume of dacite of the second stage in the main cone is the difference between 32 and 21 cubic miles, or 11 cubic miles. To this must be added 2 cubic miles of lava erupted from lateral vents, so that the total volume is 13 cubic miles.

The volume of andesite erupted during the last stage of activity is the difference between the total volume of the main cone (36 cubic miles) and the volume of the cone at the end of the fourth stage (33 cubic miles), or 3 cubic miles.

The total volume of lava erupted from both the main and secondary vents is as follows:

Total volume of lava erupted from San Francisco Mountain.

	Cubic miles.
Latite (lava, breccia, and tuff)	21
Pyroxene dacite (lava)	13
Hornblende dacite (lava)	½
Rhyolite (lava)	½
Andesite (lava)	3
	38

PROPORTION OF CONE ERODED SINCE CESSATION OF VOLCANIC ACTIVITY.

Although the ravines and serrated crest line create the impression that the mountain has been considerably eroded, measurements do not bear out this idea. It is estimated from the restored cross sections that the present crest line is on the average 3,000 feet below the summit of the cone as it stood at the close of volcanic activity. This means that the height has been reduced over one-third, a very considerable amount. It must be remembered, however, that volumes are under consideration and that a large reduction in the height of a cone does not carry with it a corresponding loss in volume.

The minimum amount of erosion that has occurred is shown in section A–A′, through San Francisco and Fremont peaks; the maximum amount in section C–C′, through the interior valley and the large ravine on the west side. An intermediate amount is exhibited by section B–B′, through Agassiz Peak and Peak F. An inspection of the geologic map (Pl. V) shows that sections similar to B–B′ are the most common, and consequently that the amount of erosion of a cone generated by this section will approximately represent the average for the entire cone. It is of especial interest to know the proportion of the cone that has been eroded, because it gives a clue to the actual age of the volcano and its relative age as compared with the other cones of the region. It also permits an idea to be formed of the accuracy of estimates of the erosion that have been based only on eye observations in the field.

The least erosion, as stated above, is shown by section A–A′. It amounts to 4 per cent of the total volume of the cone generated by that cross section. For the cone corresponding to section B–B′ the proportion eroded is 6 per cent, and the maximum amount of erosion for the cone generated by section C–C′ is equivalent to 12 per cent of the total volume. The amount of erosion for the whole cone has been obtained by averaging the above values weighted according to the proportion of the cone that has been correspondingly eroded. Thus, the value for the cone generated by section A–A′ has been given a weight of 1, section B–B′ 12, and section C–C′ 5. On this basis San Francisco Mountain has lost 8 per cent of its total volume since volcanic activity became extinct. This final value does not include the erosion along a number of the ravines on the outer slopes of the mountain. A calculation shows, however, that the volume of this erosion is so small in proportion to the total erosion as to be negligible. That is to say, the ravines, with the exception of the interior valley and perhaps the one on the west side, are mere scratches on the surface of the volcano.

A check may be had on the above calculation by considering the manner in which erosion has taken place. An inspection of the cross sections and the geologic map will show that erosion has tended to reduce the height of the cone without greatly altering the slopes below. The ravines do not extend more than halfway down the slopes of the mountain, the lower slopes being in general thoroughly protected from erosion by the heavy mantle of waste material. Under these conditions the portion of the cone that remains may be considered as a frustum having a height equal to one-half the height of the restored cone. Likewise the portion removed may be thought of as a frustum of equal height. Calculated in this manner the proportion of cone eroded is 6 per cent of the total volume. The amount of erosion according to the first method of calculation—8 per cent—is one-third greater than this, so that it may be slightly in excess of the true value.

It was formerly believed that the cone had been much more severely eroded than is actually shown by this calculation. It was a surprise to find so small a figure for the actual volume of erosion. It may be instructive, therefore, to compare certain estimates of a qualitative nature that have been made regarding the degree of erosion of San Francisco Mountain with the true value in order to form an idea of their correctness.

Dutton [1] has said that the cone "has long been extinct and is greatly battered by erosion." Salisbury [2] says: "San Francisco Mountain is another example of a volcanic mountain partially destroyed by erosion. The form of the old cone can be but imperfectly known." D. W. Johnson [3] describes the mountain as follows: "The once symmetrical form of the volcano has

[1] Op. cit., p. 120.
[2] Salisbury, R. D., Physiography, 1907, p. 384.
[3] A recent volcano in the San Francisco Mountain region: Bull. Geog. Soc. Philadelphia, vol. 5, No. 3, 1907.

been so much dissected by streams and glaciers that we may regard it as in a more or less mature stage of its erosion history." The first two descriptions clearly imply extensive erosion. It may be a matter of doubt just how much erosion is necessary to produce a more or less mature stage of development of a volcanic cone having 20° slopes. Maturity of form, however, results from the entire consumption of the intervalley slopes, and in the case of San Francisco Mountain, with the ravines spaced as they are, this would be associated with extensive erosion. These descriptions exhibit a common tendency to greatly overestimate the erosion of the cone and indicate that ideas regarding the extent of erosion of this mountain have been quite inaccurate when based simply on a general field view.

It would not be surprising to find that the extent of erosion of volcanic cones, and possibly other mountain types, in arid and semiarid regions has been and is likely to be very generally overestimated. Dutton, for instance, applied the same description to Mount Taylor, in New Mexico, as he did to San Francisco Mountain. The cross sections of Mount Taylor, showing minimum and maximum erosion, are compared with the corresponding sections of San Francisco Mountain in figure 8. A rough calculation places the amount of erosion of the Mount Taylor cone at 11 per cent of the total volume, which hardly warrants the expression "greatly battered by erosion." This error is caused, perhaps, by the bare and rugged upper slopes being too strongly impressed upon the mind, whereas the lower uneroded slopes covered with alluvium are overlooked. Furthermore, not all the ravines of volcanoes, which play an important part in forming an idea of the extent of erosion, are due to erosion. They not uncommonly result from original differences in the positions of separate flows.

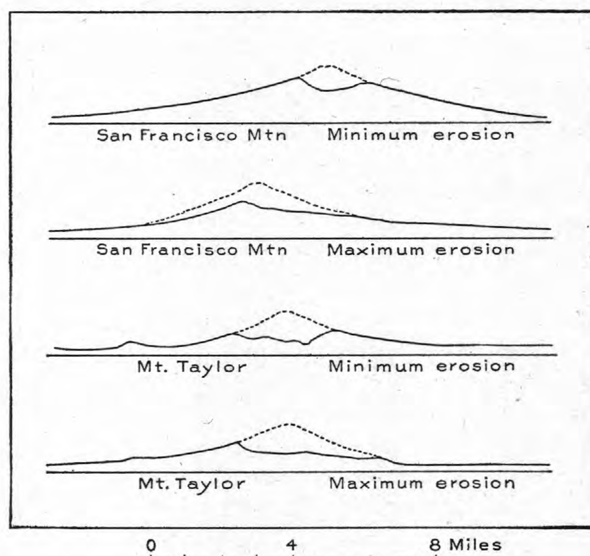


FIGURE 8.—Comparative erosion of San Francisco Mountain and Mount Taylor.

PLATFORM OF THE VOLCANO.

The exposures on the flanks of Elden Mountain and Marble Hill show that at these two localities the platform on which San Francisco Mountain stands is the basalt-covered surface of the plateau. The basalt is that of the first general period of eruption of the region and was somewhat eroded before San Francisco Mountain was formed. Thus it is probably more correct to say that the cone rests partly on the basalt, partly on the underlying sedimentary rocks. It is certain that the cherty Kaibab limestone (Pennsylvanian) lies beneath the mountain, and possibly Permian (?) and Triassic strata are also present. Broadly speaking, beds belonging to the Shinarump group lie east of a line from the north end of Anderson Mesa to Slate Mountain and the cherty limestone lies west of it, and this line passes beneath the volcano. But at the two nearest localities—Elden Mountain and Marble Hill—where sedimentary rocks are exposed, only cherty limestone is present, so that the strata beneath the volcano can not be precisely determined. A fissure located in the north wall of the interior valley of the mountain is filled with numerous pieces of greenstone, porphyry, and siliceous sediments embedded in a soft fine-grained matrix of a light-brown color. The fragments of red sandstone which occur in the fissure may have come either from the Shinarump group or from the lower formations of the Aubrey group. Red sandstones that can not be distinguished megascopically in small specimens are found in all these formations. For the sake of simplicity the cone has been represented in the cross sections as resting upon the basalt, which in turn lies only upon the cherty limestone.

AGE OF THE VOLCANO.

The fact that but 8 per cent of the total volume of the cone has been eroded would appear to fix the cessation of volcanic activity at no very remote date. Activity must have begun somewhat earlier in order to permit the eruption of such an extensive and well-differentiated series of lavas as occurs at San Francisco Mountain, but it is estimated that this interval was shorter than that which has elapsed since the cone became extinct. The mountain is younger than the basalt of the first general period of eruption, because its lavas overlie the basalt both at Elden Mountain and at Marble Hill. The lavas of San Francisco Mountain differ so notably from the basalt in character, mode of eruption, and extent of erosion that they have been assigned to an entirely distinct period, which is called the second general period of eruption of the San Franciscan volcanic field.

SUMMARY.

San Francisco Mountain is a composite volcano both with respect to the character of its material and the variety of its lavas. At the close of activity the summit rose 8,800 feet above the surface of the plateau and the base covered an area of about 110 square miles. Its total volume was 38 cubic miles.

Erosion has now lowered the height of the cone on the average 3,000 feet, so that no trace of the former crater remains. A large valley has been excavated on the east side of the mountain for 3½ miles from its center, completely breaching the wall of the cone down to the level of 8,500 feet. This valley was occupied by a small glacier during a recent period, as is shown by the well-developed moraines and outwash plain. The outer slopes are scored by a number of smaller ravines, from the mouths of which alluvial material has been spread out in a series of coalescing fans. Both the ravines and the fans are noticeable features in the topography of the mountain. The fans border the base of the cone for over two-thirds of its circumference and on the south and west sides extend more than halfway up the slopes. Although the cone has the appearance of being considerably eroded, calculations show that but 8 per cent of the total volume has been removed since it became extinct.

The structure of the volcano is clearly made out from the position of the beds exposed in the walls of the interior valley and on the outer slopes. They dip away on all sides from a central mass of igneous rock at the head of the interior valley, which is thus identified as the neck of the cone. The rocks here exposed show that all the principal vents were situated in close proximity to one another at this locality. Over 90 per cent of the erupted lavas came from these central vents, and this accounts for the symmetrical outline of the volcano.

Five distinct stages of activity are recognized. They may be tabulated as follows:

Stages of activity of San Francisco Mountain.

Stage.	Type.	Lava.	Volume of lava.	Height of cone.
			Cubic miles.	*Feet.*
1	Predominantly explosive; very active	Latite (lava, breccia, tuff)	21	7,400
2	Quiet; vigorous	Pyroxene dacite (lava)	13	8,200
3	Predominantly quiet; weak	Hornblende dacite (lava)	½	8,200
4	Quiet; weak	Rhyolite (lava)	½	8,200
5	Quiet; rather vigorous	Andesite (lava)	3	8,800

The cone rests on the somewhat eroded basalt-covered surface of the plateau and so far as known has not produced any pronounced change in the attitude of the strata beneath it.

The lavas of San Francisco Mountain are younger than the basalt of the first general period of eruption, which caps the peneplained surface of the plateau, as they overlie the basalt at Elden Mountain and Marble Hill. They are older than certain other basalts which overlie them—a relation best seen in the vicinity of the schoolhouse on the Grand Canyon road west of the mountain. These basalts have been erupted from small cones and are elsewhere found resting on the basalt of the first general period of eruption. The lavas of San Francisco Mountain therefore occupy a position between the two basalts in the volcanic sequence of the region and are assigned to a distinct period of activity—the second general period of eruption—on account of their marked difference in composition and mode of occurrence.

KENDRICK PEAK.

TOPOGRAPHY.

Kendrick Peak, the second largest cone of the region, is 11 miles northwest of San Francisco Mountain and rises 10,418 feet above sea level, or more than 3,000 feet above the surrounding country. The main mass of the mountain is distinctly symmetrical and has a characteristic

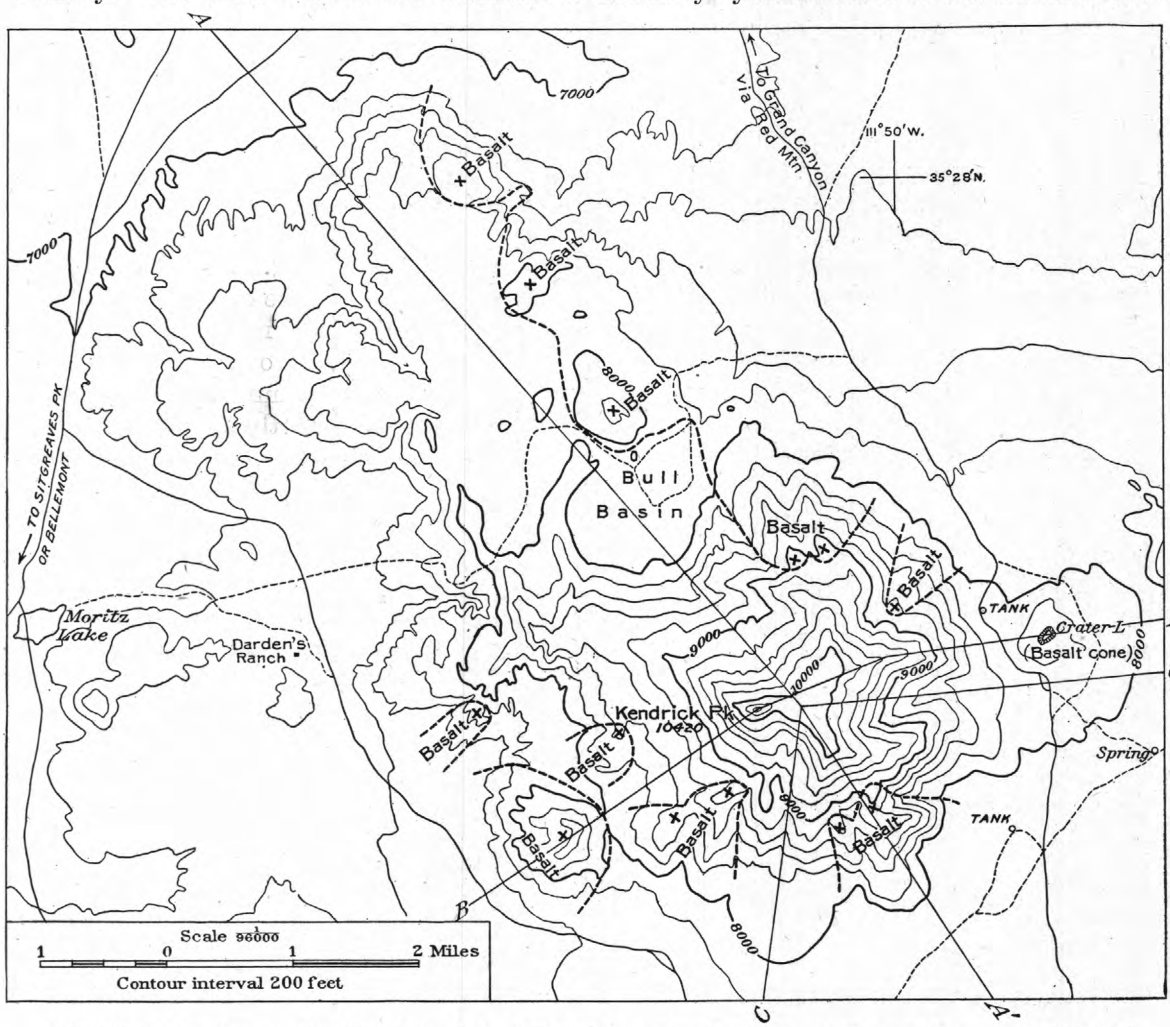


FIGURE 9.—Topographic map of Kendrick Peak. *A-A′*, *B-B′*, *C-C′*, Lines of sections in figure 10. Topography from map of Flagstaff quadrangle, United States Geological Survey.

volcanic contour. The outline appears most regular when viewed from the south (Pl. IX, *A*). It is more irreglar as seen from the north on account of a mesa-like tongue of lava and several small basaltic cones.

Since it became extinct the main cone has been reduced in height 1,000 feet. The slopes are somewhat dissected by erosion, which has resulted principally in the development of three large meridional ravines situated on the east, northwest, and south sides of the mountain. These ravines head near the geometric center of the cone and have lowered the height of the mountain vertically without shifting their divides. They are rather symmetrically spaced, the angular distances between them being 110°, 115°, and 135°. The heads of the ravines are separated by very narrow divides at an elevation of 10,250 feet, and from the extremity of the western divide the summit of the mountain rises 250 feet higher. On account of the obtuse intersection of the divides, the profile of the upper part of the cone (Pl. IX, *A*) is similar in appearance from all points of view and is thus a very characteristic feature in the topography of the volcano. The interravine slopes in general are undissected, except at high altitudes. The cone, as a whole, is in a youthful stage of its erosional history.

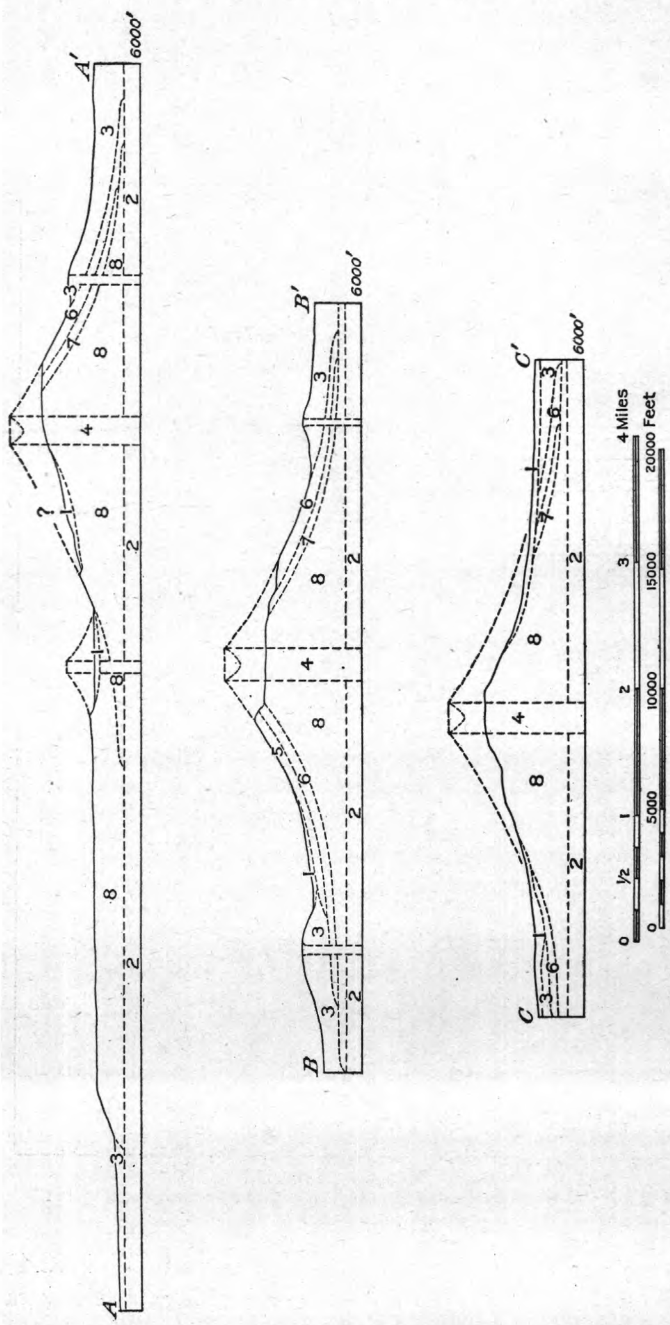


FIGURE 10.—Geologic cross sections of Kendrick Peak. For lines of sections see figure 9. 1, Alluvium; 2, Carboniferous (undivided); 3, basalt (third general period of eruption); 4, core rock (undivided); 5, andesite; 6, hypersthene dacite; 7, pyroxene dacite; 8, rhyolite; 4 to 8 belong to second general period of eruption.

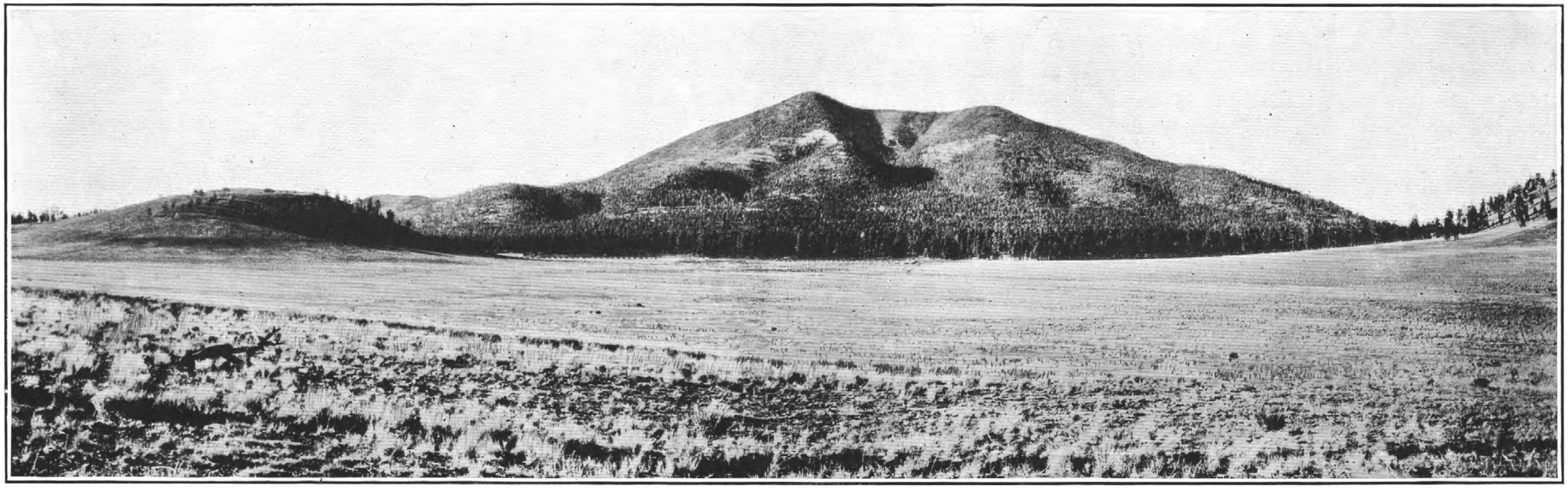
The material eroded from the upper part of the mountain has been deposited about the base as alluvial fans or in inclosed basins formed by intersecting basalt flows. Bull Basin and the alluvial areas south and southeast of the mountain are examples of such basins. They are shallow, as wells sunk in them reach lava at depths of 10 to 30 feet below the surface of the alluvial filling. Alluvium fills the ravines on the east and northwest sides of the mountain up to an elevation of over 9,500 feet and has a maximum surface slope of 10°. Evidently it must have accumulated when the rate of disintegration was largely in excess of the rate of transportation. The fans are now undergoing dissection at the higher elevations and the eroded material is being deposited beyond the base of the cone; this duplicates the condition on San Francisco Mountain.

The surface on which Kendrick Peak rests is not exposed at any locality within 6 miles of the cone, so that its nature must be judged from the general conditions that exist in the region. The mountain presumably stands on the somewhat eroded basalt-covered surface of the plateau, as does San Francisco Mountain. It is probable that the sedimentary rocks belong entirely to the cherty Kaibab limestone, as this is the youngest formation exposed at the localities nearest the cone. In the cross sections (fig. 10), for the sake of simplicity, the rhyolite is shown as lying directly on the limestone; this does not mean that the basalt is necessarily absent.

ERUPTIVE HISTORY.

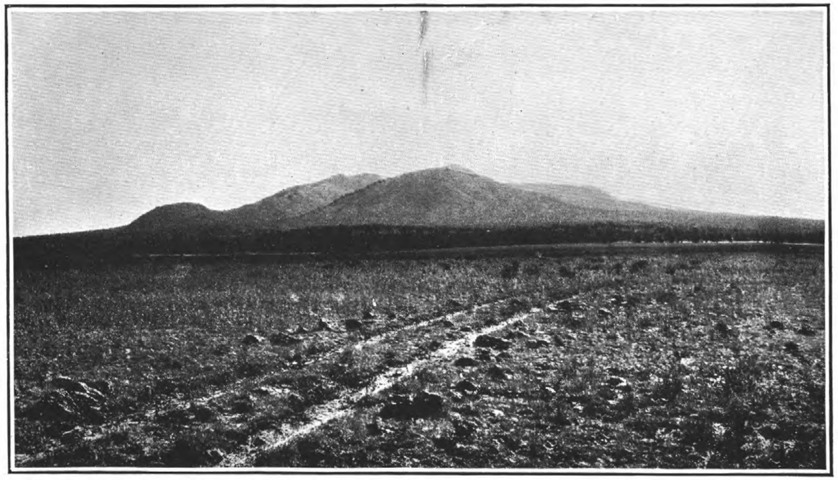
VARIETIES OF LAVA.

Kendrick Peak is a composite cone formed of five lavas which represent an equal number of eruptive stages. It is a simple cone, however, with respect to the material that composes it, as it consists entirely of lava flows. The lavas in order of eruption are rhyolite, pyroxene



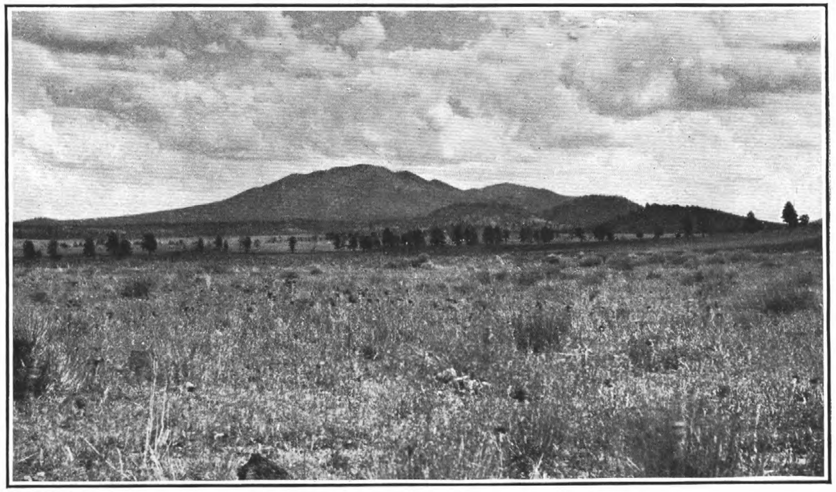
A. KENDRICK PEAK FROM THE SOUTH.

The low rounded knobs on the lower slopes are basalt of the third general period of eruption, as are the small cones in the middle distance on both sides.



B. BILL WILLIAMS MOUNTAIN FROM THE WEST.

Main summit is in the background. Small secondary cone on north slope. Walls of main cone cut on south and west by ravines.



C. SITGREAVES PEAK FROM THE WEST.

Small basalt cones of third period of eruption in middle distance.

dacite, hypersthene dacite, andesite, and basalt, the succession being without break from an acidic rock to one of basic composition. An idea of the chemical composition and differentiation of the lavas may be obtained from the following partial analyses:

Partial analyses of lavas from Kendrick Peak.

	Rhyolite.	Pyroxene dacite.	Hypersthene dacite.	Andesite.	Basalt.
SiO_2	68.8	62.0	60.4	56.5	47.4
Al_2O_3	15.2	17.0	17.0	16.3	16.4
Fe_2O_3	2.7	2.7	2.1	2.9	3.4
FeO	1.7	2.7	3.9	5.1	7.7
MgO	.7	2.4	3.0	4.1	8.6
CaO	1.7	4.0	4.4	6.1	10.4
Na_2O	4.4	4.0	3.8	3.9	2.5
K_2O	3.7	3.1	3.0	2.2	.8
TiO_2	0.3	.9	1.0	1.5	1.5
	99.2	98.8	98.6	98.6	98.7

As the analyses show, the rhyolite, dacites, and andesite are slightly more basic than the corresponding lavas of San Francisco Mountain, which is due to regional differentiation. They have, however, the same megascopic characters as the lavas of the San Francisco cone. Even the rhyolite has typical spherulitic and glassy textures, although in chemical composition it more closely resembles the dacites than the rhyolite of San Francisco Mountain. It is interesting to note that the two dacites have practically the same chemical composition but differ slightly as to their dark minerals, thus duplicating the dacites of San Francisco Mountain.

Basalt eruptions occurred at 12 or more points in the immediate vicinity of Kendrick Peak, and a number of vents were well up on the slopes of the main cone. If observations were confined to Kendrick Peak this basalt would be included in the same period of activity as the more acidic lavas. Wider observations show, however, that it should be correlated with the basalts of the succeeding general period of eruption. It will not be further considered in the description of the cone.

FIRST STAGE OF ERUPTION.

The rhyolite erupted during the first stage of activity forms over three-quarters of the main mass of Kendrick Peak and covers more than 9 square miles of country to the northwest. It is most extensively exposed in the main cone on the divide between the eastern and northwestern ravines and about the head of the eastern ravine. The exposures consist mostly of light-grayish spherulitic and black glassy flows intimately interbedded. The thinner glassy layers are commonly broken up and the fragments included in the spherulitic lava, thus forming a flow breccia. At the outer end of the northeast divide the rhyolite has an average strike of N. 70° W. and a dip of 15° to 35° N. At the same locality, just above the contact with the pyroxene dacite, is a thick flow of black, lustrous obsidian. Its strike is N. 35° W. and its dip 35° W. Near the contact with the dacite at the inner end of the southeast divide the average strike of the rhyolite is N. 65° E. and the dip 25° to 35° N. The exposures between these two localities have highly variant attitudes, the strikes ranging from N. 25° E. to N. 80° W., the dips from 15° to vertical. Smaller exposures of rhyolite in the main cone occur at three points on the north slope and at one point on the south slope. The lava at these localities is somewhat more compact than that on the divides and the dips indicate that it came from a centrally located orifice. At the locality on the south slope the rock has a dense aphanitic texture and in thin section is seen to be holocrystalline; it has evidently been recrystallized in the presence of heated water or vapor.

The strike of the rhyolite at the outer end of the northeast divide and the inner end of the southeast divide shows that the lava was erupted from a vent situated near the point of intersection of these divides. The directions of the flows at other points also intersect at about this same locality, which is at the center of the cone. The dip of the lava at the points on the divides above mentioned is toward the center of the cone, so that the exposures must be in the rim of a crater. The outcrops between the two divides fall within the area of the vent thus indicated, which accounts for their highly diverse strikes and dips. The exact size and shape of the orifice can not be determined owing to the covering of soil, but the diameter can not be much over a quarter of a mile.

The rhyolite northwest of the mountain forms a mesa-like mass which rises 250 feet above the surrounding basalt. The actual thickness of the lava, however, must be nearly 1,000 feet, if the surface on which it rests has been correctly located. The restoration of Kendrick Peak shows that, although the lowest flows of this locality may have come from that cone, by far the greater part of the lava was erupted from two independent cones of smaller size.

One of these cones is situated at the northwest foot of Kendrick Peak. Its south side is partly covered by later dacite flows, a fact which proves that the eruptions at this vent were contemporaneous with those of the first stage of the main cone. The rim is continuous on the south and west sides but is lacking on the north. The lava which issued from this orifice covers about 2 square miles southwest of the cone. It differs from the rhyolite elsewhere on Kendrick Peak in its lighter color—a delicate pearl-gray—and its more pumiceous structure. The light color of the lava makes this cone and its associated flows conspicuous in views of Kendrick Peak from the west.

The existence of the second cone has to be inferred. A cone is supposed to have been situated on the site of Bull Basin because of the circular form of that depression and the structure of the ridge bounding it on the northwest. (See figs. 9 and 10.) This ridge is composed of a light lilac-colored rhyolite, containing phenocrysts of light-brown biotite, exactly similar to the lava forming the mesa to the northwest. The strike of the lava conforms to the curvature of the ridge and the dip is 10° to 20° NW. As may be seen from cross section A–A′ (fig. 10), it is quite impossible to restore Kendrick Peak on the assumption that the lava in this ridge came from the main vent, and moreover there is no rhyolite of this character found in the large cone. The reconstruction of the cone on the site of Bull Basin has thus been made as shown in section A–A′. The indicated form is purely conventional. It is probable that the original cone was lower and that its removal was due to forces of a catastrophic nature rather than simply to erosion.

It is estimated from the restorations of the mountain that the main rhyolite cone was originally about 4,600 feet high and its volume 3.6 cubic miles. In addition 1.7 cubic miles of lava was erupted from the vents on the north, so that the total volume of rhyolite was 5.3 cubic miles. As the total volume of all the lavas at this locality was 6.2 cubic miles, it will be seen that the Kendrick Peak eruptions consisted predominantly of rhyolite.

SECOND STAGE OF ERUPTION.

The pyroxene dacite of the second stage outcrops on the northeast and southeast divides, where it overlies the rhyolite. The greatest thickness—500 feet—is on the southeast divide, so that the initial overflow occurred at this point. This lava is also the surface rock of the northwest slope and extends to the base of the mountain. The flow abuts against the small rhyolite cone, which partly obstructed and changed its course. So far as the exposures go, it can be said only that the dacite overran the sides of the older rhyolite cone on the east and northwest. It may have covered them on the south and west, but it did not do so on the north side. At that locality the hypersthene dacite of the succeeding stage rests directly on the rhyolite.

The vent from which the lava escaped can be located only in a general way, from the directions of the flows, as just west of the rhyolite core. There are, however, no exposures at this locality by which its size and shape might be determined.

The lava of this stage for the most part is compact and light to dark gray or brown in color. An aphanitic groundmass contains phenocrysts of plagioclase and pyroxene. At some points, especially on the northwest slope, small segregations containing hornblende occur, which are of interest as suggesting the origin of the dark-colored basic inclusions in the dacites at other localities in the region.

THIRD STAGE OF ERUPTION.

The hypersthene dacite of the third stage is the surface rock to a greater or less extent on all sides of the cone except the northwestern. There the pyroxene dacite of the preceding stage and possibly the rhyolite rose to a height which prevented its overflow. Where it is not covered by basalt, the lava is seen to extend to the base of the cone and it is probable that it extended farther beyond the base than the lavas of the preceding stages. The directions of the flows point to the location of the vent about a quarter of a mile northeast of the present summit of the mountain. The area was not visited, as it appeared to be quite lacking in outcrops.

The hypersthene dacite is typically dark gray in color, rarely almost black. An aphanitic groundmass contains numerous phenocrysts of feldspar and a few of pyroxene. This rock is generally distinguished from the dacite of the preceding stage by its darker color. However, as the color of the lavas is variant, the two may be confused in some hand specimens.

The restoration of the cone shows that during this stage it reached its maximum height of 4,800 feet and probably extended to its greatest basal area. The volume of lava erupted is estimated at 0.6 cubic mile, which gave the cone a total volume of 4.4 cubic miles.

FOURTH STAGE OF ERUPTION.

The andesite of the fourth and last stage of activity of Kendrick Peak occurs only as a few small flows at the summit and on the west slope. The vent from which it escaped was not located, but from the position of the flows it must have been near the vents of the preceding stages at the center of the cone. This lava is more compact and dense than the other lavas, and because of its greater resistance to erosion it now caps the summit of the mountain.

VOLUME OF THE CONE AND OF THE INDIVIDUAL LAVAS.

The total volume of the cone has been calculated from five restored cross sections, three of which are shown in figure 10, in the same manner as that of San Francisco Mountain. The results are as follows:

Volume of cone of Kendrick Peak.

Cone generated by—	Cubic miles.
Cross section A–A′	4.56
Cross section B–B′	4.12
Cross section C–C′	4.72
Cross section D–D′	4.06
Cross section E–E′	4.72
Average	4.5

The differences in the individual volumes are of the same order of magnitude as those of San Francisco Mountain, and show that the two cones possess the same degree of symmetry.

The volume of the rhyolite cone of the first stage of activity has been calculated from two cross sections with the following results:

Volume of rhyolite cone of Kendrick Peak.

Cone generated by—	Cubic miles.
Section A–A′	3.23
Section B–B′	3.54
Average	3.4

If the erosion indicated by exposures on the east side of the rhyolite cone is taken into account, the above result may be increased by 5 per cent, which makes the volume of the original cone 3.6 cubic miles, to which must be added 1.7 cubic miles of lava erupted from the secondary vents, so that the total volume of the rhyolite is 5.3 cubic miles.

The total volume of the two dacites and the andesite must be 1.1 cubic miles, the difference between the final volume of the main cone (4.5 cubic miles) and that of the eroded rhyolite cone (3.4 cubic miles). This has been apportioned among the three lavas on field evidence, without calculation, as follows: Pyroxene dacite, 0.4 cubic mile; hypersthene dacite, 0.6 cubic mile; andesite, 0.1 cubic mile.

PROPORTION OF CONE ERODED SINCE CESSATION OF ERUPTIONS.

The impression that Kendrick Peak is less eroded than San Francisco Mountain is probably created by the smaller scale on which the details of the topography are developed and by the absence of any striking erosional feature such as the interior valley of the larger mountain. Calculations show, however, that the same relative proportion of the total volume of both cones has been removed and strengthen the belief that estimates of such erosion are of doubtful value when based only on field views.

The minimum amount of erosion is exhibited in section B–B′ (fig. 10). It is 3.5 per cent of the total volume of the cone generated by that section. The maximum erosion is along the line of section C–C′, and is equivalent to 20 per cent of the volume of the corresponding cone. An intermediate value of 6.5 per cent is obtained from section A–A′. An average value of 5 per cent is obtained from four cross sections exclusive of section C–C′. From an inspection of the topographic map of the mountain (fig. 9), it is estimated that if the average value be given a weight of 4 and the maximum value a weight of 1, a fair average for the entire cone will be obtained. On this basis, then, the proportion of the main cone of Kendrick Peak that has been eroded since volcanic activity became extinct is 8 per cent of the total volume.

AGE OF THE CONE.

The only field evidence as to the relative age of the volcano is the fact that the acidic lavas underlie a basalt and are consequently older. From the fact that the cone has experienced the same proportionate erosion as San Francisco Mountain, and from the close similarity of their lavas and mode of eruption, it is certain that the two cones were formed at the same time. The lavas of Kendrick Peak are thus definitely placed in the second general period of eruption of the region.

SUMMARY.

Kendrick Peak consists entirely of lava flows erupted during four separate stages of activity. The cone attained a maximum height of 4,800 feet and covered an area of 40 to 50 square miles. The volume of the main cone was 4.5 cubic miles; including the lava from secondary vents, it was 6.2 cubic miles.

Erosion has lowered the height of the cone about 1,000 feet and developed three large meridional ravines on the south, the east, and the northwest sides. At other localities the slopes in general are largely undissected. Alluvial fans cover the lower slopes and similar material fills a number of small basins about the foot of the mountain. The proportion of the main cone that has been eroded since it became extinct is 8 per cent of the total volume.

The four stages of activity may be tabulated as follows:

Stages of activity of Kendrick Peak.

Stage.	Type.	Lava.	Volume.	Height of cone.
			Cubic miles.	*Feet.*
1	Active and vigorous	Rhyolite	5.3	4,400
2	Quiet, weak	Pyroxene dacite	.4	4,600
3	Quiet, weak	Hypersthene dacite	.6	4,800
4	Quiet, weak	Andesite	.1	4,800

The greatest activity occurred during the first stage, and, as shown by the volumes, the cone consists predominantly of rhyolite. The succeeding eruptions produced little change in the size of the cone, but the lavas form an interesting sequence in comparison with those of the other large volcanoes of the region. No fragmental material was observed at Kendrick Peak, and the eruptions throughout were probably quiet.

The cone most probably rests upon eroded remnants of the basalt of the first general period of eruption and the cherty Kaibab limestone.

The lavas of Kendrick Peak are older than the basalt of the third general period of eruption. They are placed in the second general period of eruption of the region on account of their close similarity to the lavas of San Francisco Mountain and the fact that the cone they built up has suffered the same proportionate erosion.

BILL WILLIAMS MOUNTAIN.

TOPOGRAPHY.

Bill Williams Mountain lies 33 miles S. 75° W. of San Francisco Mountain and is the westernmost of the large cones included within the San Franciscan volcanic field. The mountain

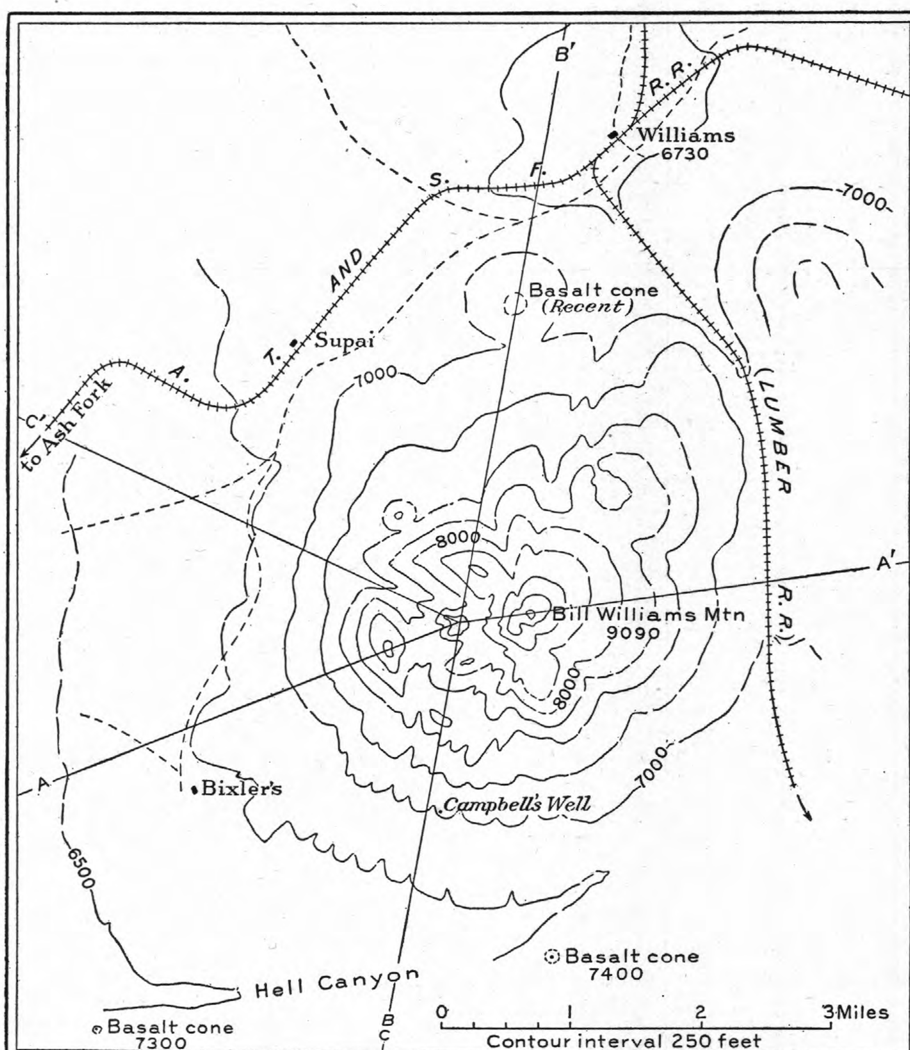


FIGURE 11.—Topographic map of Bill Williams Mountain. A–A', B–B', C–C', lines of sections in figure 12. Topography by H. H. Robinson, 1903.

rises about 9,100 feet above sea level or 2,400 feet above its foot slopes and if the lavas belonging to secondary vents are included, it constitutes the third largest center of eruption in the region.

Bill Williams Mountain is less symmetrical than the other large cones, except Mormon Mountain, owing to the presence of secondary cones on the outer slopes and the manner in which the mountain has been eroded. It is not difficult, however, to recognize the volcanic origin of the mass, even in its present condition, for the general conical form is still preserved, as may be seen from the sketch map (fig. 11). The map emphasizes the symmetry of the cone with respect to a central point, a feature that is not so evident in the field. In the view from Williams the mountain presents a rather irregular outline, the summit rising behind several dome-shaped peaks of lower altitude. A more symmetrical outline is presented in views from the west (Pl. IX, *B*), the several peaks then clearly appearing as the eroded remnants of a single large volcano, with a secondary cone 500 feet high on the lower northwest slope.

The cone is somewhat dissected. The present summit is 800 feet and the crest line, as a whole, about 1,300 feet below the original summit. The southern rim is the most eroded and on the northwest and southwest sides the walls are cut by two large ravines that head at the center of the cone. The mouths of these ravines are well up on the slopes of the mountain at an elevation of 7,500 feet, where the alluvial fans begin. The boundaries between flows from secondary vents and those from the main orifice fix the position of several smaller ravines on the north and east sides of the cone, but erosion along these lines has been rather slight. The interravine slopes are essentially uneroded, showing that the mountain is in a youthful stage of dissection.

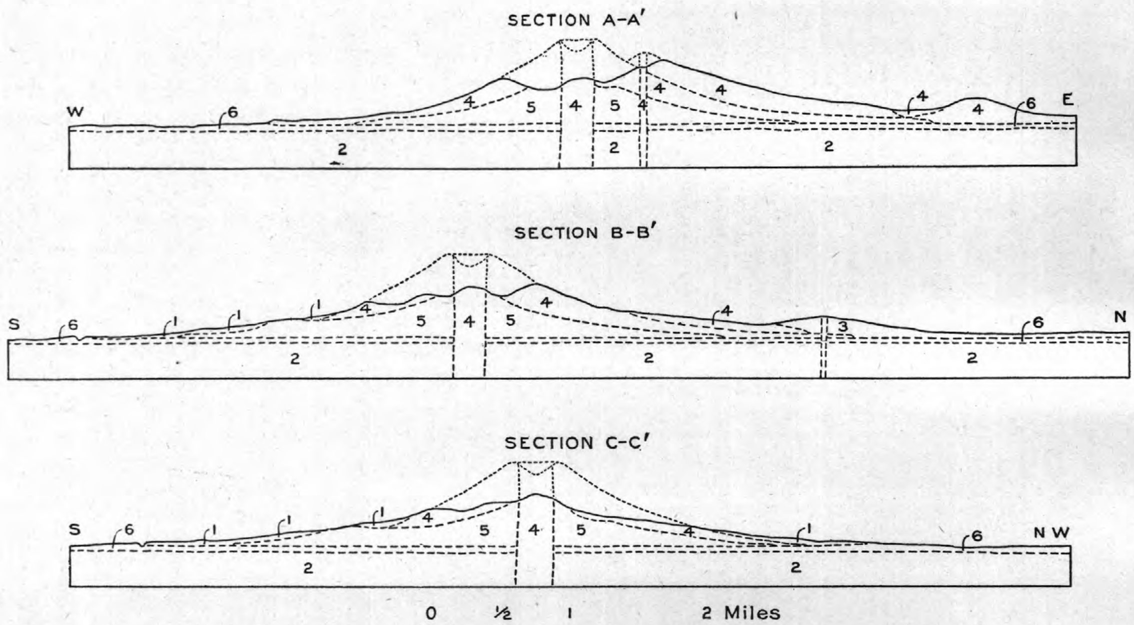


FIGURE 12.—Geologic cross sections of Bill Williams Mountain. 1, Alluvium; 2, Carboniferous formations (undifferentiated); 3, basalt of third general period of eruption; 4, dacite of second general period of eruption; 5, andesite of second general period of eruption; 6, basalt of first general period of eruption. For lines of sections see figure 11.

Alluvial fans cover the slopes on the south and west sides up to an elevation of 7,500 feet. The dissection of the fans on the south side is especially noticeable. Washes 10 to 25 feet deep cut the alluvium at an average space of 1,000 feet from its upper to its lower limit. The continuity of the alluvium with the lava slope above it has been broken in some places by lateral erosion at the heads of the washes, thus giving rise to what might be called hogbacks of alluvium. The washes are sharply intrenched and the interwash slopes are uneroded, a condition which clearly indicates a youthful stage of dissection. It is evident that although aggradation exceeded transportation when the material was laid down, at present the relationship is reversed. This is true at all the large cones.

ERUPTIVE HISTORY.

VARIETIES OF LAVA.

Bill Williams Mountain is a composite cone formed by lavas and breccias of two distinct stages of eruption. The distribution of the material shows that about two-thirds of it escaped from centrally located vents and built a symmetrical cone, and that the remainder came from secondary orifices situated either on the slopes or about the base of the volcano. The lavas in order of eruption are andesite and dacite. Their chemical composition may be judged by the following partial analyses:

Partial analyses of lavas from Bill Williams Mountain.

	Andesite.	Dacite.
SiO_2	51.5	66.0
Al_2O_3	17.2	16.1
Fe_2O_3	4.6	2.3
FeO	5.5	1.8
MgO	6.0	1.5
CaO	8.1	3.6
Na_2O	3.4	4.7
K_2O	1.7	2.9

Both lavas correspond in their chemical and mineral characters, as well as in appearance, to the andesites and dacites that occur elsewhere in the region, and they unquestionably belong to the same general period of activity. The andesite is, however, somewhat more basic in composition than the related lavas of San Francisco Mountain and Kendrick Peak and in some respects resembles the basalt of the succeeding period. The dacite of Bill Williams Mountain and that of San Francisco Mountain and vicinity are so nearly alike in megascopic appearance that they may be easily confused.

FIRST STAGE OF ERUPTION.

Andesite in the form of breccia outcrops at the heads of the ravines at the center of the mountain and at the northern base east of the small dacite cone. In the form of lava flows it is found in the vicinity of Campbell's well and Bixler's ranch, on the south and west sides of the mountain. It may occur at other localities about the base of the cone, but the region was not examined in sufficient detail to reveal them. The attitude of the beds at the localities mentioned shows that most of the material came from a central vent which later was the main channel of escape for the dacite. The vent, to judge from the dacite plug, must have been approximately circular in form and somewhat over 500 feet in diameter. The elevation of the lava at Campbell's well (section B–B′, fig. 12) suggests a secondary outbreak on the slope of the main cone, unless the restored outline of the andesite cone is much in error. All the observed exposures, as shown by the cross sections, represent material erupted during the last third of this stage of activity, and breccia is present in greater amount than lava. Explosive phases, therefore, exceeded in number those of a quiet nature, and it is inferred that the relation prevailed throughout this initial stage of activity. The restoration of the cone indicates that it had an original height of about 2,100 feet and a volume of 0.8 cubic mile.

SECOND STAGE OF ERUPTION.

The dacite of the second stage outcrops in many beds on the inner slopes of the mountain and forms the greater part of the outer slopes. It also composes the group of small detached cones east of the main cone. At all these localities it is in the form of flows. Fragmental material (pumice) was observed only in the valley through which the lumber railroad runs, on the east side of the mountain.

The position of the vent from which the flows outcropping on the inner slopes of the cone were erupted is fixed, half a mile west of the present summit of the mountain, by a circular plug of lava 800 feet in diameter. Erosion has removed the surrounding lava and breccia down to an elevation of 8,000 feet, and the core now rises with steep slopes 100 feet on the east side and over 250 feet on the west side above the divide between the two interior ravines. It is clearly expressed in the topography of the cone, as may be seen from the map or cross sections. The core rock does not differ markedly in appearance from that of the flows. It is, however, somewhat more compact and in mass shows a definite vertical flow structure.

Much of the lava which forms the outer slopes and therefore was erupted during the later part of the stage came from secondary orifices. The cones built by these eruptions are noticeably dome-shaped, and the flows form prominent ridges on the slopes. The irregular outline of the mountain, as seen from Williams, is due to such eruptions, and the present summit of the mountain is formed by the lava from one of the secondary vents (section A–A′, fig. 12). The positions of three secondary vents, along a north-south line a quarter of a mile east of the central core, are marked by plugs. Small cones on the lower northwest and northeast slopes fix the positions of two other vents. Other secondary orifices are marked by the group of dome-shaped hills at the east base of the mountain.

The dacite on the north and west sides extends 2 to 3 miles from the center of the cone. The steep fronts of these flows show that the lava never extended much beyond its present position. There is, however, one isolated remnant of dacite, about a mile north of Williams and just east of the railroad to the Grand Canyon, whose relation to lavas of Bill Williams Mountain was not determinable. The outcrop is entirely surrounded by basalt and rises 25 feet above it. The lava is dark gray in color, is compact, and contains very few phenocrysts; it does not especially resemble the dacites of Bill Williams Mountain.

The second stage of activity may evidently be divided into two parts, and the succession of events is very similar to that determined for the second stage of eruption of San Francisco Mountain. During the first part the eruptions came from a single central vent. It is estimated that 1 cubic mile of lava was thus erupted and that the cone was built up to a height of 3,200 feet. At this time the form of the volcano, to judge from the parts now exposed, was very symmetrical, the slopes being slightly concave and smooth. The restorations show that the slopes of this cone are steeper than those of the andesite cone of the preceding stage, which expresses the more viscous condition of the dacite. During the later part of the second stage there was a dispersion of vents, and eruptions occurred from at least seven secondary orifices on the outer slopes or about the base of the main cone. They added nothing to the height of the main cone and only slightly increased its volume. In all, however, 1.2 cubic miles of lava was erupted from secondary vents, most of it from those at the base of the cone, making the total volume of dacite 2.2 cubic miles. From the forms of the cones it is inferred that the lava of the later eruptions was more viscous than that of the earlier outbreaks. In the absence of any change in the composition of the lava, this difference suggests that the temperature of the magma decreased as volcanic activity came to a close at this locality. The eruptions of the entire second stage in general were quiet, although at least one explosive phase is revealed by the pumice on the east side of the mountain.

VOLUME OF THE CONE AND OF THE LAVAS OF THE TWO STAGES.

The erosion of the volcano has been so slight that the former outline may be easily restored and a basis secured for calculating the volume. For this purpose the three cross sections (fig. 12) have been used in the same manner as those of San Francisco Mountain. The volume of the cone built up by eruptions from the central main vents is as follows:

Volume of cone of Bill Williams Mountain.

Cone generated by—	Cubic miles.
Section A–A′	1. 64
Section B–B′	2. 00
Section C–C′	1. 87
Average	1. 8

The volume of the andesite cone is as follows:

Volume of andesite cone of Bill Williams Mountain.

Cone generated by—	Cubic miles.
Section A–A′	0. 63
Section B–B′	1. 00
Average	. 8

The volume of dacite erupted from the main vent is 1 cubic mile, the difference between the above two averages. To this must be added the lava of the lateral vents on the outer slopes and about the base of the mountain, which is roughly calculated at 1.2 cubic miles, making a total volume of 2.2 cubic miles of dacite.

PROPORTION OF CONE ERODED SINCE CESSATION OF VOLCANIC ACTIVITY.

The same proportion of the cones generated by sections A–A′ and B–B′ has been eroded and equals 7 per cent of the total volume. This nearly represents the minimum amount of erosion. The maximum amount is shown by section C–C′, and the proportion of the corresponding cone that has been removed is 14 per cent of its total volume. It is estimated from the topographic map that a fair average is obtained by giving the minimum value a weight of 2½ and the maximum a weight of 1. On this basis the proportion of the cone eroded since activity ceased is 9 per cent of the total volume. This is practically the same value as that obtained for San Francisco Mountain and Kendrick Peak.

AGE OF THE CONE.

The lavas of Bill Williams Mountain overlie on the west side the basalt of the first general period of eruption, and underlie on the north side the basalt of the third general period. They are therefore intermediate in age. As the cone has been eroded to the same proportionate extent as San Francisco Mountain, and as the lavas at the two volcanoes are similar, Bill Williams Mountain should clearly be assigned to the second general period of eruption.

SUMMARY.

Bill Williams Mountain is a composite cone built up by lavas and breccias of two separate stages of activity. The eruptions came in part from central vents, in part from lateral orifices on the outer slopes or near the base of the cone. The eruptions from the lateral orifices deformed what would otherwise have been a cone as symmetrical as those of San Francisco Mountain and Kendrick Peak. At the close of activity the volcano was 3,200 feet high and covered an area of about 25 square miles. The volume of all the lavas was 3 cubic miles.

Erosion has lowered the height of the cone on the average about 1,300 feet. The southern rim is eroded the most, and two large ravines on the southwest and northwest sides extend to the center of the cone. Alluvial fans mantle the lower slopes and are now undergoing dissection. Of the total volume of the volcano 9 per cent has been eroded since it became extinct.

The stages of eruption may be tabulated as follows:

Stage.	Type.	Lava.	Volume.	Height of cone.
			Cu. miles.	*Feet.*
1	Predominantly explosive, active, and vigorous	Andesite	0.80	2,100
2	Predominantly quiet, active, and vigorous	Dacite	2.20	3,200

The cone rests on the eroded basalt-covered surface of the cherty Kaibab limestone.

The lavas were erupted after the basalt of the first general period of eruption but before that of the third period. They are assigned to the second general period of eruption because of their similarity to the andesites and dacites elsewhere in the region and because the cone of Bill Williams Mountain has been eroded to the same proportionate extent as the cones of San Francisco Mountain and Kendrick Peak.

O'LEARY PEAK.

TOPOGRAPHY.

O'Leary Peak lies 9 miles northeast of San Francisco Mountain and is the easternmost of the large cones. The highest peaks rise 8,925 feet above sea level, or about 2,500 feet above Deadman Wash on the northwest. On the south and east, however, surrounding basalt cones reduce the relative height of the mountain to about 1,800 feet.

In views from the north and south the profile of the mountain is double (Pl. I, *A*, p. 16), owing to the overlapping of two separate cones. From the west, when the smaller cone is hidden behind the larger, the mountain appears to be a single volcano. The outlines of the two parts are symmetrical and approximately conical in shape. The slopes of both cones, except at their extremities, average 25°. The slopes of the larger cone, however, are slightly concave, whereas those of the smaller one are slightly convex and the summit is dome shaped. The cones are bare of vegetation and are covered with a thin mantle of disintegrated lava through which ledges protrude at many points. The summit of the larger cone is marked by two peaks that are separated by a narrow saddle 200 feet lower in elevation. The two principal ravines of this cone are on the north and south sides and head at this saddle.

It is estimated from restored outlines made on photographs of the larger and more recent cone that the height of the mountain has been reduced about 700 feet. This is considerably less than the reduction of 1,300 feet determined for Bill Williams Mountain, which is of about the same size. The impression derived from field views is that O'Leary Peak has been less eroded. The rainfall is less at O'Leary Peak than at Bill Williams Mountain because the locality is farther from the edge of the plateau and is also cut off from the rain-bearing winds by San Francisco Mountain. It is probable that this climatic condition has existed for a long period and that it may account for the apparently less eroded state of this cone.

ERUPTIVE HISTORY.

VARIETIES OF LAVA.

O'Leary Peak is formed by two cones composed of different lavas and representing distinct stages of activity. So far as known only lava is present at this locality, and its distribution shows that most of it was erupted from central vents. There are, however, some small masses at the southwest base of the mountain that came from secondary orifices. The lavas in order of eruption are rhyolite and dacite, having the composition shown by the following partial analyses:

Partial analyses of lavas from O'Leary Peak.

	Rhyolite.	Dacite.
SiO_2	67.0	62.3
Al_2O_3	16.5	16.4
Fe_2O_3	2.3	2.9
FeO	2.1	3.3
MgO	.5	2.1
CaO	2.0	3.8
Na_2O	5.1	4.3
K_2O	3.3	3.2
TiO_2	.4	1.0
	99.2	99.3

Both lavas are megascopically counterparts of the rhyolites and dacites that occur elsewhere in the region. They are also mineralogically similar to these rhyolites and dacites. Chemically, however, they are somewhat more basic, especially the rhyolite, on account of regional differentiation. The relationship of these lavas to similar but more acidic lavas is evident and places them in the second general period of eruption.

FIRST STAGE OF ERUPTION.

The rhyolite of the first stage of eruption is found in two cones of unequal size. The larger cone forms the eastern part of the main mass of O'Leary Peak; the smaller one is situated on the edge of the O'Leary lava field 2 miles S. 75° W. of the summit of the mountain. The rhyolite also occurs in flows which cover about 2 square miles north of the mountain. Flows may have extended in other directions, but if so they have been buried under the basalts of the succeeding period of eruption. The larger cone was not closely examined, but its dome-shaped form shows that the lava was extruded in a rather viscous condition. It is estimated that the original height of this cone was 2,700 feet and its volume 0.5 cubic mile. Only the summit of the smaller cone now protrudes above the surrounding dacite and basalt. The original height of this cone was about 1,200 feet and the volume 0.1 cubic mile.

The lava of the main rhyolite cone, where it was examined at the north foot of the mountain, is a finely banded dark-brown felsite. The rhyolite of the smaller cone, so far as exposed, consists of a black semilustrous glass and a light-gray aphanite, with intermediate varieties due to mixtures of the two. The obsidian was erupted after the lithoidal variety.

SECOND STAGE OF ERUPTION.

Dacite forms the western and greater part of the main mountain. The relation of the dacite and rhyolite cones was not determined. It is supposed that a part of the latter is buried beneath the former, as shown on cross section C–C′ of San Francisco Mountain (Pl. VI, p. 40). The height of the cone is estimated to have been 3,500 feet. The lava occurs in flows west and northwest of the mountain, where it forms a prominent mass with steep slopes rising 100 to 200 feet above the level of Deadman Wash. The rock exposed in the saddle between the two highest summits and in the upper part of the southern ravine probably belongs to the core of the volcano. It weathers into small pinnacles, and in thin section the groundmass, although very fine grained, shows no sign of flow structure. The dacite at the southwest base of the mountain likewise exhibits no flow structure in thin section and is supposed to represent a small viscous eruption from a secondary vent.

The lava shows the common tendency of the dacites of the region to occur in heavy compact flows free from scoriaceous surfaces. It appears, in general, to contain a larger proportion of plagioclase phenocrysts; in some specimens they form one-third of the rock. Inclusions of a dark-colored microcrystalline igneous rock are very common in the flows on the west side of the mountain. In places they make up from one-tenth to one-half the area of small exposures. They were evidently taken up in a solid condition by the dacite, for the contacts are always perfectly sharp and well defined.

VOLUME OF THE CONE AND OF THE TWO LAVAS.

A reliable calculation of the volume of the lavas of O'Leary Peak is not possible. Approximate results may be obtained, however, by considering the volcanoes as perfect cones with 25° slopes and heights as given in the preceding description. On this basis the volume of the two rhyolite cones is 0.6 cubic mile. In addition there is 0.3 cubic mile in flows, making a total of 0.9 cubic mile for the lava of the first stage of activity. The volume of the complete dacite cone is 1.3 cubic miles, which is reduced to 1 cubic mile to allow for the portion of the rhyolite cone supposed to underlie it. The volume in flows is estimated at 0.2 cubic mile, making the total 1.2 cubic miles for the lavas of the second stage of eruption. The total volume of the lavas of O'Leary Peak, therefore, is 2.1 cubic miles.

SUMMARY.

O'Leary Peak is a double cone built up by lavas during two separate stages of activity. The eruptions came predominantly from a single vent in each stage, but there were several minor orifices near the bases of the main cones. At the close of activity the volcano was 3,500 feet high and covered an area of about 15 square miles. The volume of the two lavas was approximately 2.1 cubic miles.

The dacite cone appears to have been reduced in height 700 feet. The slopes are covered with a thin mantle of disintegrated lava and there are no prominent ravines, such as occur on the other large cones.

The stages of eruption may be tabulated as follows:

Stages of eruption of O'Leary Peak.

Stage.	Type.	Lava.	Volume.	Height of cone.
			Cu. miles.	*Feet.*
1	Quiet	Rhyolite	0.9	2,700
2	do	Dacite	1.2	3,500

The cones of both stages were very active and the eruptions vigorous. The rhyolite is supposed to have been decidedly viscous, as the cone has steep convex slopes. The dacite was less viscous than the rhyolite.

The platform on which the cones rest is not exposed in the immediate vicinity. It may be the eroded basalt-covered surface either of the cherty Kaibab limestone or the Shinarump group.

The lavas of O'Leary Peak are fixed by local evidence only as older than the basalt of the third general period of eruption. Their character places them in the second general period of eruption with those of the large cones already considered.

SITGREAVES PEAK.

TOPOGRAPHY.

Sitgreaves Peak is situated 19 miles west of San Francisco Mountain in line with Kendrick Peak and Bill Williams Mountain. It rises about 9,300 feet above sea level, or about 1,700 feet above the general level of Government Prairie on the southeast side. The crest of the mountain is irregular and varies in outline from different points of view; the slopes, on the contrary, are very symmetrical and gently concave (Pl. IX, *C*, p. 54). The inclination is 20° on the upper slopes and gradually decreases to less than 5° at the base of the mountain. The maximum slope at the original summit appears to have been 25°, so that the mountain as a whole had somewhat flatter slopes than the other large cones. It is estimated that the height of the cone, since it became extinct, has been reduced at least 1,000 feet and that erosion has been most vigorous on the south and east sides. The eroded material now mantles the lower slopes in large alluvial fans, which are trenched to their outer edges by numerous washes, in the same manner as the alluvium of Bill Williams Mountain.

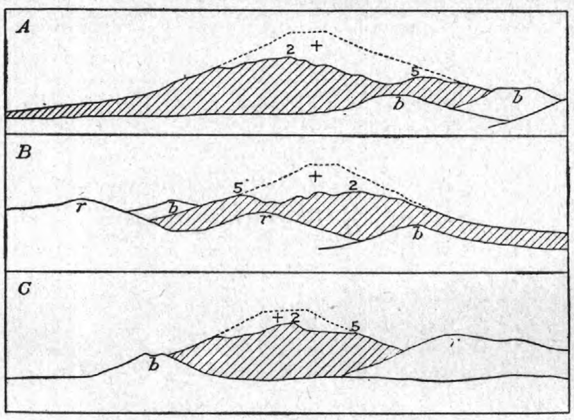


FIGURE 13.—Profiles of Sitgreaves Peak: *A*, seen from the west; *B*, from the northeast; *C*, from the southeast; *r*, rhyolite cones; *b*, basalt cones 2 and 5, corresponding peaks; +, middle point of base.

STRUCTURE OF THE MAIN CONE.

The main mass of Sitgreaves Peak was not studied in sufficient detail to permit any exact conclusion as to its structure. Restorations made on photographs show that the mountain is most probably a simple cone built up about a central vent (fig. 13). The profiles were completed by first restoring the upper slopes, the summit or crater being given a diameter of 1,000 feet. The lower slopes were then projected downward to the inferred level of the platform on which the cone rests. The middle point of the base in each section, marked by a cross, falls within the assumed position of the crater, and this coincidence suggests a simple structure for the cone. A detailed field examination might disclose minor lateral vents on the slopes such as were associated with the main orifices at the other large cones. An outcrop of agglomerate containing fragments of sedimentary rocks, which is exposed at the southeast base of the cone near point 5 (fig. 14), probably represents an initial outbreak from a secondary vent. It is situated about 600 feet above the inferred level of the platform on which the main mass of the cone rests, and at this altitude elsewhere on the slopes only lava is found.

ERUPTIVE HISTORY.

Sitgreaves Peak consists wholly of rhyolite and in this respect differs from all the other large cones. The eruptions built up one large cone to a height of 3,500 feet and three smaller ones from 1,000 to 1,500 feet high. Two of the latter are situated at the base of the main cone, as shown in figure 14 (A and B); the third is located 5½ miles N. 85° E. of the summit of the mountain.

The lavas of the main cone consist for the most part of light-brown and bluish felsites and a subordinate amount of black obsidian. In appearance they are the counterpart of the rhyolites that occur elsewhere in this region and are clearly to be correlated with them in the second general period of eruption. The chemical composition of the lava may be seen from the following analysis:

Analysis of rhyolite from Sitgreaves Peak.

SiO_2	74.9	Na_2O	5.6
Al_2O_3	13.1	K_2O	4.3
Fe_2O_3	.5	H_2O	.3
FeO	.8	TiO_2	.1
MgO	.2		100.1
CaO	.3		

The lavas of the small cone marked A in figure 14 dip away on all sides from a central point, where there is a mass of agglomerate composed of fragments of lavender-colored lava embedded in a lighter-colored cement. Evidently this is the core rock, and its distribution shows that the crater was not more than 300 feet in diameter. The cone, which now rises 500 feet above the level of Spring Valley, has lost some of its original height, though it is still very symmetrical in form. The slopes are almost entirely covered with loose fragments of lava and are cut by many ravines which extend with low grades nearly to the center of the cone. The lavas consist of three varieties—a dense pinkish felsite, a light lavender-colored spherulite, and a lustrous black obsidian. In general the felsite predominates in the earlier flows, the spherulitic and glassy varieties in the later ones.

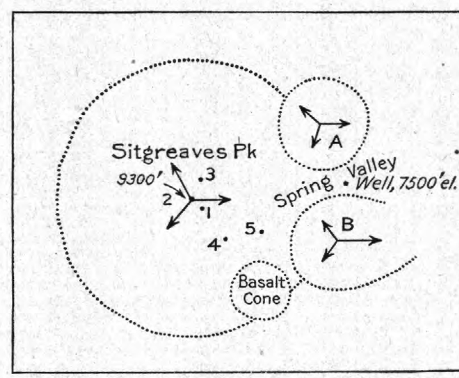


FIGURE 14.—Diagrammatic plan of Sitgreaves Peak and adjacent cones. 1 to 5, Points on main cone; A, B, smaller rhyolite cones.

Cone B (fig. 14) is composed entirely of the felsitic type of rhyolite, rather porous in texture and ranging in color from very light gray and pink to dark bluish gray. The rim of the cone is broken down on the east side, and the principal flows appear to have occurred in that direction. The third small cone contains varieties of rhyolite of the same character as those in cone B and in addition a glass finely banded in black and very dark-gray layers. There are also between cone B and the third cone several isolated knobs of rhyolite, surrounded by basalt, whose point of origin was not determined. They are too small to be shown on the general geologic map (Pl. III, p. 20).

VOLUME OF THE CONE.

The volume of the cone can not be definitely calculated. On the assumption that the cone had an original height of 3,500 feet and slopes as indicated by the restored outlines made on photographs, it is estimated that the volume was between 2 and 4 cubic miles. An average value of 3 cubic miles may be taken, which includes the volumes of the small cones.

PROPORTION OF THE CONE ERODED SINCE CESSATION OF VOLCANIC ACTIVITY.

Tentative calculations of the proportion of the cone that has been eroded have been made on the assumption that all points in the cross sections drawn on photographs are in the same vertical plane. On this basis 10 per cent of the total volume of the cone generated by section A has been eroded; 5 per cent of the cone corresponding to section B; and 2 per cent of the cone of section C. If the maximum value is given a weight of 2 and the middle value a weight of 1, an average is obtained of 7 per cent of the total volume of the cone. Although no especial accuracy is attached to this method, the results obtained are of the same order of magnitude as those for San Francisco Mountain, Kendrick Peak, and Bill Williams Mountain, which possess a fair degree of precision. The agreement is close enough to confirm the field impression that Sitgreaves Peak has been eroded to the same extent as the other large volcanoes and that it undoubtedly belongs in the second general period of eruption.

MORMON MOUNTAIN.

TOPOGRAPHY.

Mormon Mountain lies on the Black Mesa 28 miles south of San Francisco Mountain. It occupies an isolated position with respect to the other large cones, although its distance from San Francisco Mountain is less than that of Bill Williams Mountain. Its general characters show that it should be included in the second period of eruption with the large cones to the north. It is the smallest of the composite cones, rising 8,600 feet above sea level, or not more than 1,500 feet above the surrounding country. The mountain is irregular in form and elongated in nearly a north-south direction. It is designated Mount Longfellow on the United States General Land Office map of Arizona, but it is commonly known as Mormon Mountain, because a Mormon settlement was formerly located on the shore of Mormon Lake at its eastern base. Only the south slope was visited and a hurried ascent made to the summit.

ERUPTIVE HISTORY.

Two distinct stages of activity are indicated by the presence of a latite and a dacite of the following (partial) chemical composition:

Partial analyses of lavas from Mormon Mountain.

	1. Latite.	2. Dacite.
SiO_2	61.6	66.8
Al_2O_3	17.3	16.5
Fe_2O_3	2.2	3.0
FeO	2.7	.4
MgO	2.5	1.3
CaO	4.9	3.1
Na_2O	5.1	4.7
K_2O	2.2	2.5
TiO_2	.7	.4
	99.2	98.7

The megascopic characters of the two lavas point to their identity with the corresponding lavas of the other large volcanoes. The latite is duplicated in appearance by some of the flows of the first stage of eruption at San Francisco Mountain and especially by the lava of Observatory Mesa, near Flagstaff. The dacite is the counterpart of the equivalent lavas found elsewhere in the region.

By far the greater part of the mountain appears to be composed of coalescing cones of latite in thick and rather short flows. The lava is light to dark gray in color and commonly has a platy structure. Its aphanitic groundmass contains a few small phenocrysts of hornblende.

The dacite was observed as an eroded knob on the southwest side of the mountain at an elevation of 8,200 feet. Its relation to the andesite was not definitely determined. The lava dips southward coincident with the slope and may be considered either an eroded portion of a cone partly buried by later flows of latite or a small flow that broke out on the slope of the latite cone. The dacite is somewhat fresher in appearance than the latite and on this account is believed to represent a later stage of eruption.

VOLUME OF THE CONE.

No definite figure can be given for the volume of the lavas. It has been roughly placed at 2 cubic miles, of which 1.5 cubic miles is latite and 0.5 cubic mile dacite.

OBSERVATORY MESA.

Observatory Mesa extends from Fort Valley to the vicinity of Flagstaff, where the Lowell Astronomical Observatory is situated on its south end. It is 5 miles long and between 2 and 3 miles wide. The surface of the mesa has an elevation of 150 feet above Fort Valley and slopes to the southeast at an angle less than that of the surrounding country, attaining at its south end a relative altitude of over 300 feet. An irregular cliff of no great height bounds the mesa on all sides, below which is a generally well-developed talus slope. The mesa is formed entirely of lava erupted from Crater Hill, a cone 500 feet high located near its north end, and from a much smaller cone just to the east. The upper surface of the flows is somewhat decomposed and covered with a thin mantle of soil, through which protrude small bare knobs of rock.

The lava composing the cones and mesa is uniformly dense, commonly showing a platy structure, and is of a dark-gray color. In hand specimens it is rather basaltic in appearance. The specific gravity of specimens from different parts of the mass is as follows:

Specific gravity of lava from Observatory Mesa.

Crater Hill	2.71
Edge of mesa, north end	2.60
Edge of mesa, near Anderson's ranch	2.66
Edge of mesa, near observatory	2.68
Edge of mesa, south end	2.64
Average	2.65

These determinations have a variation of only 4 per cent and indicate the homogeneity of the mass. The densest lava is located at the point of eruption.

The andesite of San Francisco Mountain is in close contact with the lava of the mesa along its northeast side and has bleached it to a notable extent. This fact, taken in connection with the specific gravity and other characters of the lava, makes it certain that the lava of Observatory Mesa is equivalent to the latite of the first stage of eruption of San Francisco Mountain.

SUGARLOAF HILL.

Sugarloaf Hill is a small rhyolite cone situated on the east slope of San Francisco Mountain. The summit rises 9,281 feet above sea level, or on the average 1,000 feet above its base. A second mass of closely related rhyolite adjoins Sugarloaf Hill on the north. The two masses show very plainly in views of San Francisco Mountain from the east (Pl. VII, *A*) on account of their light color.

The summit of Sugarloaf Hill contains a roughly circular depression about 300 feet in diameter, representing the remains of a crater. The lava which now forms the rim rises less than 100 feet above the bottom of the crater, but it must originally have risen to a greater height, as the cone shows signs of considerable erosion. The flow structure of the rhyolite in the rim is very clearly marked and almost without exception dips toward the center of the depression at angles of 50° to 90°, the average of six observations being 65°. The rhyolite of Sugarloaf Hill has throughout a uniform texture, well described as pasty, and is very light gray or brown in color. Alternations of these two colors produce the banded appearance of the rock. The ground mass is aphanitic and contains small phenocrysts of quartz, feldspar, and biotite.

The rhyolite north of Sugarloaf Hill, which was erupted from an independent vent, is a low, rather dome-shaped mass. The early flows have a uniform stony texture and are light gray in color; the later ones have a pasty texture and are brown in color. An intermediate variety, formed by the alternations of the two main types, shows that the change from the first to the second took place gradually.

The rhyolite at this locality was erupted before the andesite of San Francisco Mountain, as that lava overlies it on the south side of Sugarloaf Hill. It also appears to antedate the dacite of the second stage of activity, which abuts against the smaller mass of rhyolite and bulges out to the east around its north end in a manner strongly suggesting that it met an obstruction to the normal northeastward course of flow (Pl. V, p. 40). If this interpretation is correct, the rhyolite of Sugarloaf Hill was not contemporaneous with the rhyolite of the fourth stage of activity of San Francisco Mountain, although the two vents are but 4 miles apart.

DRY LAKE HILLS.

The Dry Lake Hills lie between San Francisco and Elden mountains and consist of about five small cones of dacite. The lava is similar to the dacites found elsewhere in the region, but was probably more viscous, as the cones are distinctly dome shaped. Two of the larger cones have crater-like depressions at their summits, and a shallow lake occupies one of these depressions when conditions are favorable.

The dacite overlies the basalt of the first general period of eruption at a point half a mile northeast of the Flagstaff reservoir. It also appears to have been erupted after the formation of Elden Mountain. This relation may be seen at the northwest foot of Elden Mountain, a little over half a mile north of Doyle's spring, where the two lavas approach the closest to one another (fig. 15). A narrow tongue of dacite from the Dry Lake Hills dies out 75 feet from the base of Elden Mountain. It appears less eroded than the lava of Elden Mountain and is therefore considered younger. The irregular diagonal boundary of the dacite of the Dry Lake Hills on the northward-sloping surface of the northern sedimentary block of Elden Mountain is interpreted as signifying the same relation. A mantle of alluvium effectually hides all other contacts and makes it impossible to say whether the lavas of the Dry Lake Hills were strictly contemporaneous with the dacites of San Francisco Mountain, but in view of their exact similarity it may be assumed that they were erupted during the second or third stage of activity of the San Francisco volcano.

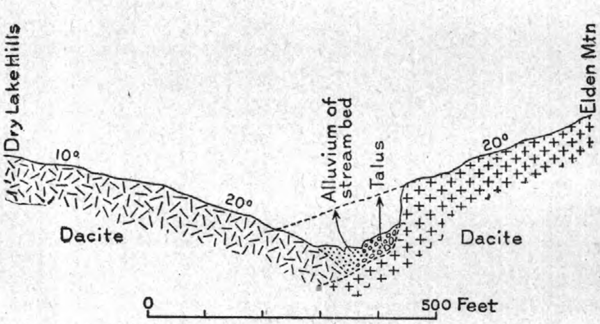


FIGURE 15.—Cross section of valley half a mile north of Doyle's spring, showing relation of lavas of Dry Lake Hills and Elden Mountain.

LACCOLITHS OF THE SECOND PERIOD.

Three masses of igneous rock are included in the laccolithic group, but only one of them, Marble Hill, is a true laccolith. Elden Mountain, which approaches the large cones in size, exhibits in a unique manner laccolithic intrusion and volcanic extrusion as contemporaneous phenomena in the same geologic unit. The origin of Slate Mountain is doubtful because of insufficient field work; it may be similar to that of Elden Mountain. Though these masses possess no little interest in themselves, they have a specific local interest on account of the presence on the flanks of Elden Mountain and Marble Hill of upturned lavas from San Francisco Mountain, by means of which their position in the sequence of events in the San Franciscan volcanic field may be definitely determined.

MARBLE HILL.

Marble Hill is a normal laccolith of small size situated on the lower northwest slope of San Francisco Mountain, 3½ miles from San Francisco Peak. It rises 9,065 feet above sea level, but as the surrounding country has an elevation of 8,000 to 8,500 feet, the relative relief is only 800 feet. The base, as marked by the enveloping mantle of waste, is nearly circular in form and covers an area of 1.5 square miles. The hill consists of a central peak, which is the main summit, almost completely encircled by a series of hills and ridges whose elevations range from 8,500 to 9,000 feet. This circle of hills lies from a quarter to half a mile from the central peak and is separated from it by a marked depression. Its continuity is unbroken except at two points on the north side, where the interior drainage escapes into Deadman Wash (fig. 16).

The summit of the central hill is composed of a granite porphyry, delicate gray in color and with a uniform compact texture. An aphanitic groundmass contains a few small phenocrysts of feldspar and biotite. The intrusive nature of the porphyry is very evident, as the limestone with which it is in contact has been completely changed to a coarse-grained white marble. A series of sedimentary and effusive igneous rocks, which forms the remainder of the hill, overlies the porphyry. A limestone outcrops on the lower slopes of the central peak and on the north-

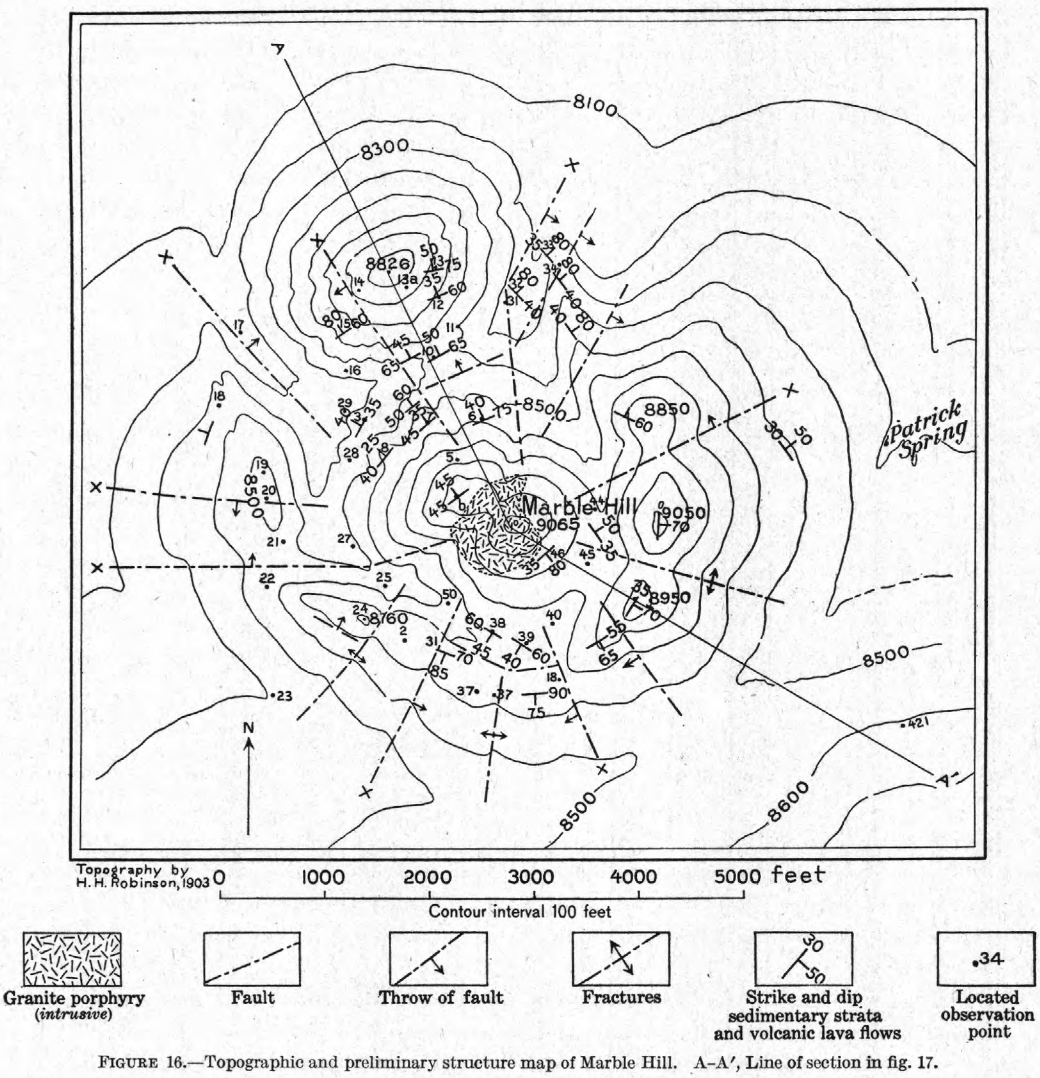


FIGURE 16.—Topographic and preliminary structure map of Marble Hill. A–A′, Line of section in fig. 17.

west side rises nearly to the same height as the igneous rock. Above the limestone, stratigraphically, and occupying the lower ground between the central peak and surrounding hills, are sandstones. The lower ones are red in color, rather soft, and even-bedded; the upper ones are white and cross-bedded. A cherty limestone rests upon the cross-bedded sandstone, and overlying this limestone are lava flows, which cap the summits of all the higher encircling hills. The sedimentary series is made up of Carboniferous formations. The lavas belong to both the first and the second general periods of eruption. The measurement of the section is made somewhat difficult by the faulting and crushing of the strata. The following table gives the formations present, in descending order, and their average thickness.

Section measured at Marble Hill.

	Feet.
Pyroxene dacite	150
Latite	10
Basalt (lava and ash)	130
Kaibab limestone (cherty)	240
Coconino sandstone (cross-bedded)	570
Supai formation (red sandstone)	670
Redwall limestone	180
	1, 950

The sedimentary strata, with the overlying lavas, have been upturned to very high angles by the intrusive rock, as may be seen from the recorded observations on the map (fig. 16). The average dip is 60°, and three-quarters of the measured outcrops have dips of 50° or greater. The strata are concentrically arranged about the igneous core, as is plainly brought out by the strike observations recorded on the map. The position of the core, however, is not exactly at the center of the circle of outlying hills, but is rather nearer the southeast side. This indicates the slightly unsymmetrical character of the intrusion, which has tilted the strata more steeply on the south than on the north side of the core.

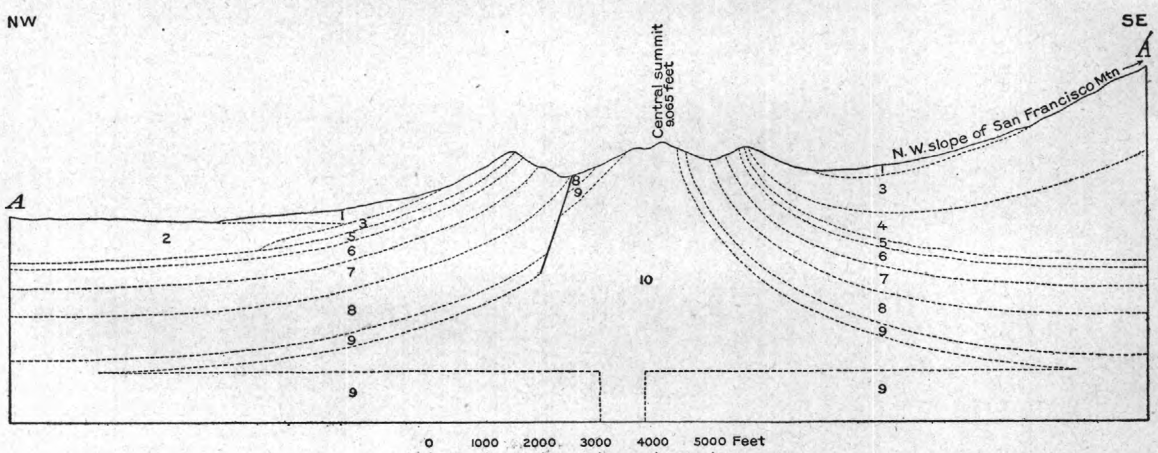


FIGURE 17.—Geologic cross section through Marble Hill: 1, Alluvium; 2, basalt of third period; 3, pyroxene dacite; 4, latite; 5, basalt of first period; 6, Kaibab limestone; 7, Coconino sandstone; 8, Supai formation (red sandstone); 9, Redwall limestone; 10, granite porphyry. For line of section see figure 16.

Radial faulting and fracturing are most easily recognized and the position and direction of throw of fourteen such planes of dislocation are indicated on the map. They all extend at least to the foot slopes of the hill and most of them radiate directly from the igneous core. Although in a strict sense the cover is divided into fourteen blocks, if fractures are disregarded and successive blocks with the same direction of throw be grouped together, a system of eight blocks remains in which alternate blocks are either raised or lowered with respect to each other. The faults that bound these blocks are marked on the map by crosses at their outer ends. Concentric faults are also present, as shown by the contiguity of strata belonging to different horizons. It seems reasonable to suppose that there should be a considerable number of such faults. They are difficult to locate, because they are parallel to the strike of the strata and their throw may not be sufficient to bring diverse beds into contact. The dislocations in the cover of the Marble Hill laccolith have been duplicated experimentally by Howe,[1] who says, in a discussion of variations dependent on passive agents in laccolithic intrusion:

> Fractures initially radial and secondly concentric tend to form in frangible strata over a symmetrical dome, the radial fractures gaping upward and the concentric ones downward.

The structure of the laccolith along a northwest-southeast line through the summit is shown in cross section A–A′ (fig. 17), and may be briefly described. On the southeast side of the igneous

[1] Howe, Ernest, Experiments illustrating intrusion and erosion: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 3, 1901, p. 302.

core the Redwall limestone dips 80° SE., the basalt which caps the encircling hill dips 70°, and the dacite at the outer foot slope has a dip of 50°; this shows the extent to which the doming dies out on this side in a distance of 1½ miles. The dip on the northwest side is 45° in the Redwall limestone, though in the overlying formations it is from 35° to 50°. Along this particular section there is thus a marked difference in the dip of the strata on either side of the intrusive core. The apparent thickness of the red sandstone of the Supai formation, northwest of the porphyry, is but 200 feet, whereas the actual thickness is placed at 670 feet. The discrepancy is due to faulting, which has raised the beds on the side next to the porphyry. The fault plane is shown in figure 17 with a westward dip to express the idea that the beds were sheared by the unsymmetrical intrusion of the igneous rock. The strata on the southeast side of the core, from being upturned to nearly vertical angles, have suffered a great contraction in thickness. Formations that have a thickness of 1,950 feet on the northwest side of the core are but 1,100 feet thick on the southeast side, the difference being 40 per cent of the normal thickness of the section. As the force of intrusion was exerted largely in a vertical direction, the contraction must have been produced for the most part by shearing and faulting closely parallel to the bedding planes.

Any attempt to restore the eroded portion of the cover will show that it must have been greatly shattered and that a favorable opportunity was presented for the escape of the igneous material in the form of surface flows. The fact that it did not so escape indicates a nice balance between opposing forces and suggests that the magma was distinctly viscous. The high viscosity of the igneous mass is most plainly indicated, however, by the absence of dikes, although the numerous radial and concentric fault planes presented favorable conditions for their intrusion. The shape of the igneous mass is clearly pluglike in its upper part, and the mass might be considered as representing a transition form between a normal domed laccolith and a volcanic neck. What would have happened to the cover if the igneous body had established free connection with the surface is of course purely conjectural. Certain possibilities, however, suggest a structure not unlike that postulated by Von Buch in his theory concerning "craters of elevation."

The eroded portion of the cover is not restored on the cross section (fig. 17), because no satisfactory idea of its original condition can be formed. The representation of the lower part of the igneous mass is of course purely conventional and designed simply to show its laccolithic nature. It has been suggested that the igneous rock is throughout pluglike in form. This, however, is impossible, because the Redwall limestone at the points where it outcrops at the surface of the country is 4,000 feet above its normal position. As a topographic map was not available when the locality was visited, the work was not so detailed as was later shown to be desirable. The Marble Hill laccolith, on account of its small size and the completeness with which the phenomena of intrusion are exhibited, offers an interesting field for further study.

Marble Hill may be very closely correlated with San Francisco Mountain, and its position in the sequence of events in the volcanic field thus fixed, by means of the upturned lavas upon its flanks. These in ascending order are basalt, latite, and pyroxene dacite. The basalt, which is the same as that found on the north flank of Elden Mountain and at many other localities in the region, belongs to the first general period of eruption of the San Franciscan volcanic field. The latite and dacite are the same in all respects as the corresponding lavas in San Francisco Mountain, and undoubtedly originated at that volcano during the first and second stages of activity. In addition to the above lavas, two dikes are exposed on the west and south sides of the central peak. One is composed of typical pyroxene dacite. The rock of the second dike, south of the summit, is essentially the same as that of the first, but contains phenocrysts of hornblende and biotite instead of pyroxene. This feature, it is believed, marks it as equivalent to the hornblende dacite of the third stage of activity in San Francisco Mountain. As the granite porphyry of Marble Hill is almost identical in chemical composition with the rhyolite of San Francisco Mountain, it seems reasonable to regard these rocks as contemporaneous and to suppose that the laccolith was formed during the fourth stage of eruption in San Francisco

Mountain. The absence of the andesite of the fifth stage of activity on the slopes of Marble Hill tends to confirm the correctness of the above correlation, for had the intrusion occurred after that stage the andesite would very probably be found upturned with the older lavas.

The evidence indicates very clearly, then, that the Marble Hill laccolith was completely formed during a single stage of activity in San Francisco Mountain. This stage—the fourth—was perhaps the shortest in the history of the volcano, so far as the time necessary for the eruption of the lava was concerned. The entire length of the period from the close of the third to the beginning of the fifth stage is unknown, but it must have been very brief in a geologic sense.

ELDEN MOUNTAIN.

SITUATION AND TOPOGRAPHY.

Elden Mountain is situated at the southeast foot of San Francisco Mountain 4 miles northeast of Flagstaff. It rises in its highest summit 9,280 feet above the sea, or 2,400 feet above the surrounding country on the south and east, and covers an area of about 10 square miles. The greater part of the mountain consists of igneous rock in dome-shaped masses. There are, however, extensive areas of sedimentary strata on the east and north sides that are intimately associated with the igneous rock and constitute an integral part of the mountain. It may be said that the mountain displays in an unusual manner laccolithic intrusion and volcanic extrusion as contemporaneous phenomena in the same geologic unit.

The extent of the erosion of the mountain varies at different localities, depending on the character and position of the rocks. It has been greatest in the eastern area of sedimentary strata; these are now surrounded on all sides but the east by a higher rim of igneous rock, although formerly the reverse relation held true. Erosion of the igneous rock has been extensive in the space between the two sedimentary areas, where a breccia is present, but outside of this locality it appears to have been relatively slight. The extent of erosion on the southwest slope of the mountain and the manner in which it is proceeding may be seen in Plate X, *A*. The slopes are scored by sharply incised ravines of youthful appearance, which by headward and lateral cutting are lowering the height of the mountain and consuming the slopes. Alluvial fans spread out from the mouth of every ravine; they head from a third to half way up the slope, depending on the size of the ravine, and, coalescing at the base of the mountain, entirely surround it. These features are common to all the large cones of the second general period of eruption, and the field impression is that Elden Mountain has been eroded to proportionally the same extent as the large cones.

IGNEOUS ROCK.

The igneous rock is throughout a dacite, identical in mineral and chemical composition with the dacites of San Francisco Mountain. It is mineralogically the same as the lavas of Schulz Peak and the Dry Lake Hills and is presumably chemically the same as those rocks, although they have not been analyzed.

The chemical composition of the rock is given by the following analysis:

Analysis of dacite from Elden Mountain.

SiO_2	65.9	Na_2O	4.5
Al_2O_3	17.1	K_2O	3.1
Fe_2O_3	4.7	H_2O	.4
FeO	.2	TiO_2	.5
MgO	.9		
CaO	2.6		99.9

The small amount of ferrous iron indicates the complete alteration of the dark minerals, a condition characteristic of the mass. The mineral composition is constant, the rock consisting of 8.5 per cent of dark constituents and 19 per cent of plagioclase feldspar (Ab_1An_1) as phenocrysts in a predominantly feldspathic holomicrocrystalline groundmass. The

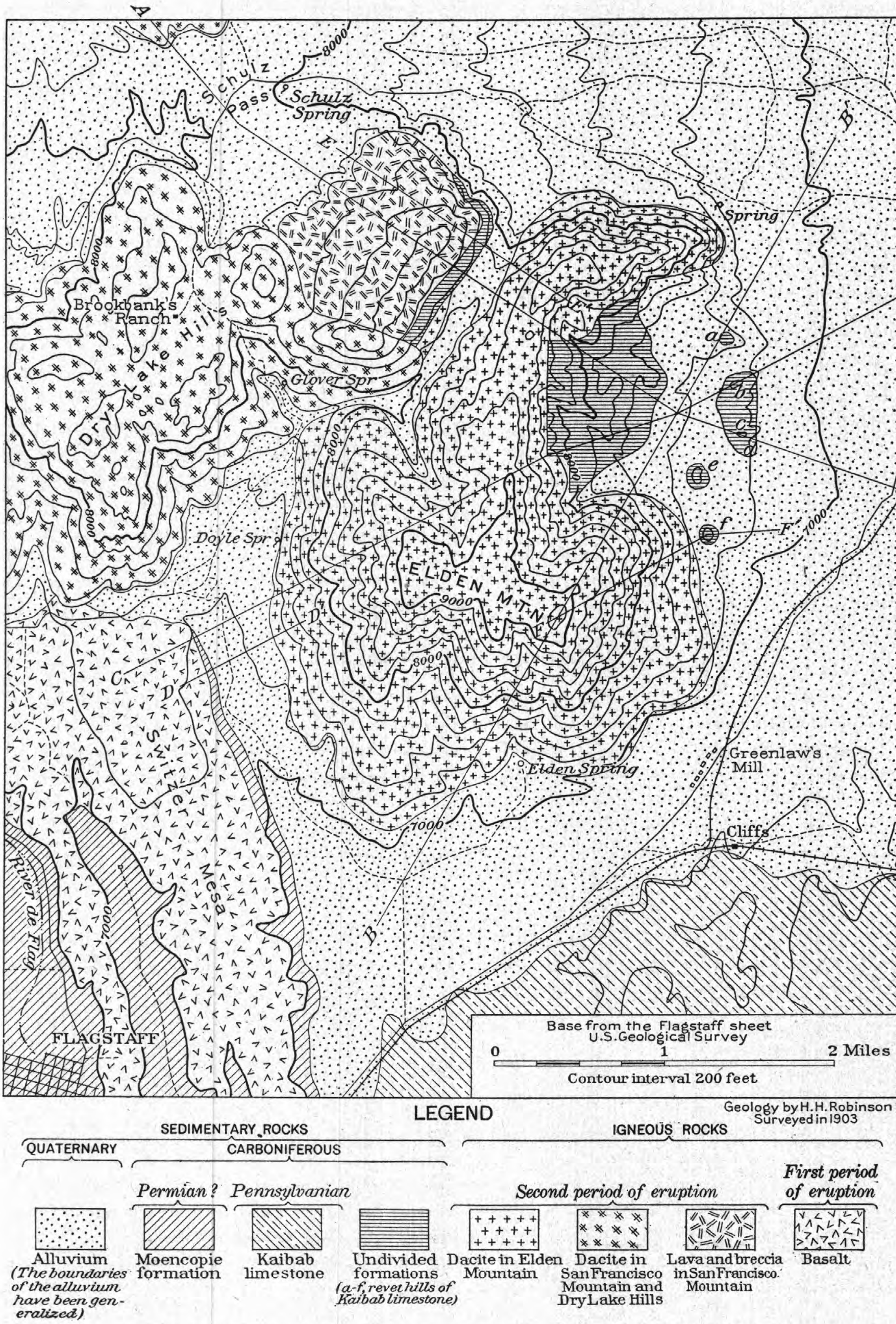


FIGURE 18.—Geologic map of Elden Mountain. A-A′, etc., Lines of cross sections in figures 19–21, 23.

groundmass exhibits almost no evidence of flow structure. This is in distinct contrast to the conspicuous flow structure shown by the hypercrystalline groundmasses of the dacites at all the other localities in the region with the partial exception of O'Leary Peak. The rock has a uniform texture and in large masses shows an apparent megascopic banding which is best brought out by differential weathering (Pl. X, *B*). Scoriaceous surfaces are entirely lacking and the rock may be said to possess a massive appearance. It was presumably this feature that led Lieut. Whipple[1] to speak of Elden Mountain as a "huge mass of red granite."

The most evident feature of the igneous rock, however, is the jointing, which is developed on a much larger and more pronounced scale than in the dacites elsewhere. The intersecting joint planes form irregular columns, having a maximum diameter of 20 feet, with rounded tops produced by greater weathering along the joints (Pl. X, *B*). The joints at any one locality vary in direction, but generally two principal planes may be distinguished which intersect at about 90° and have vertical or steep dips. At some places there is also a third plane parallel to the slope, and the intersection of this plane with the first set produces obliquely truncated columns. Examples may be seen on the eroded southern edge of the slope east of the northern summit and also on the south side of the mountain. Whether this third plane is of primary or secondary origin was not determined, nor was the study of the joint system broad enough to permit a statement of its relation to the igneous mass as a whole. Between the northern summit of the mountain and the edge of the sedimentary block to the south the igneous rock is not so thoroughly jointed; it appears more massive than elsewhere and has been eroded into prominent pinnacles.

The dacite of Elden Mountain has the same chemical and mineral composition as the other dacites of the region. Its distinctive features have not resulted, therefore, from any peculiarity in these respects, so that they must be due to special conditions in regard to the temperature and rate of cooling of the mass.

SEDIMENTARY ROCKS.

The sedimentary rocks occur at two distinct localities, one on the east and the other on the north side of the mountain. They will be described separately.

These are the only localities at Elden Mountain where the strata are found upturned by the intrusion of igneous rock. Elsewhere outcrops of sedimentary rocks are very scarce about the immediate foot of the mountain. On the south side horizontally bedded Kaibab limestone approaches within a mile, and on the west the basalt-covered Moencopie formation, also horizontally bedded, is distant about half a mile from the base of the mountain.

EASTERN SEDIMENTARY AREA.

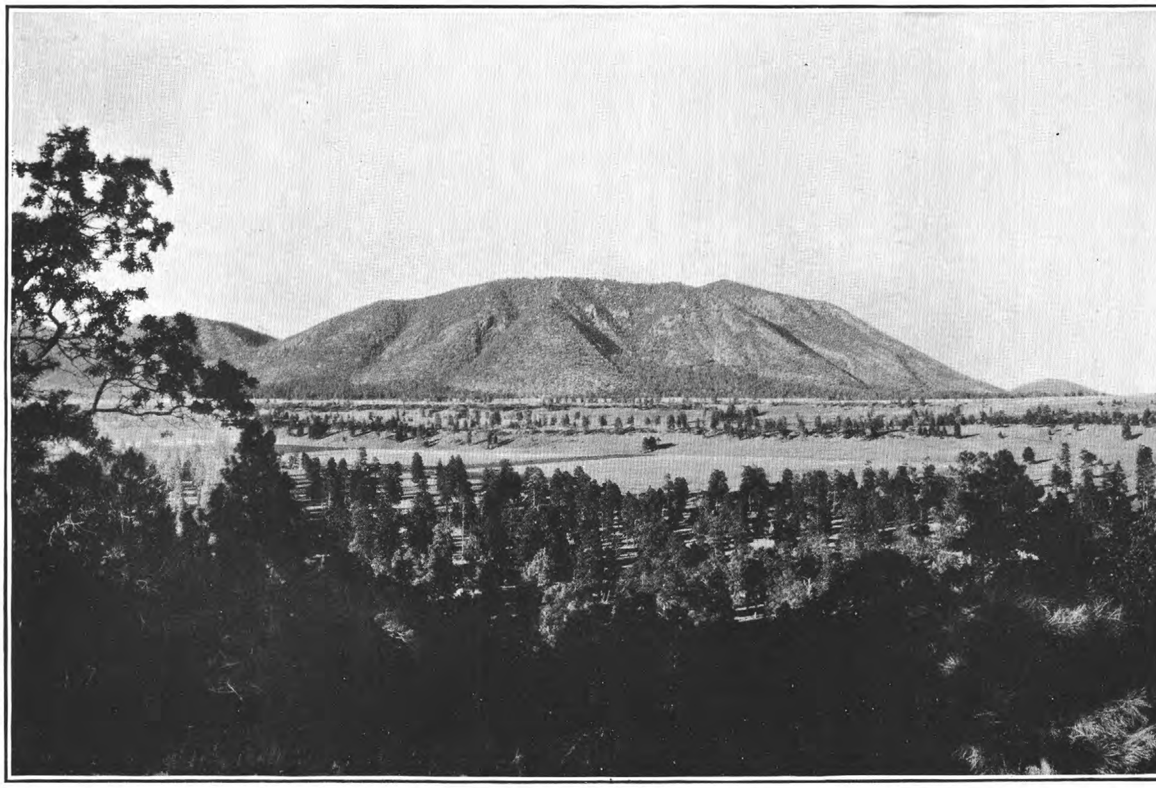
The exposures are more extensive and represent a larger number of formations on the east side of the mountain, where they cover an area of about 1 square mile. The formations present (see pp. 20–37) in descending order, are as follows:

		Feet.
Kaibab limestone (top eroded)		300
Coconino sandstone	(not separated because of faulting)	1,300
Supai sandstone		
Redwall limestone; actual thickness exposed		300

These formations all belong to the Carboniferous period. A basalt, which will be referred to later, caps the Kaibab limestone at several localities.

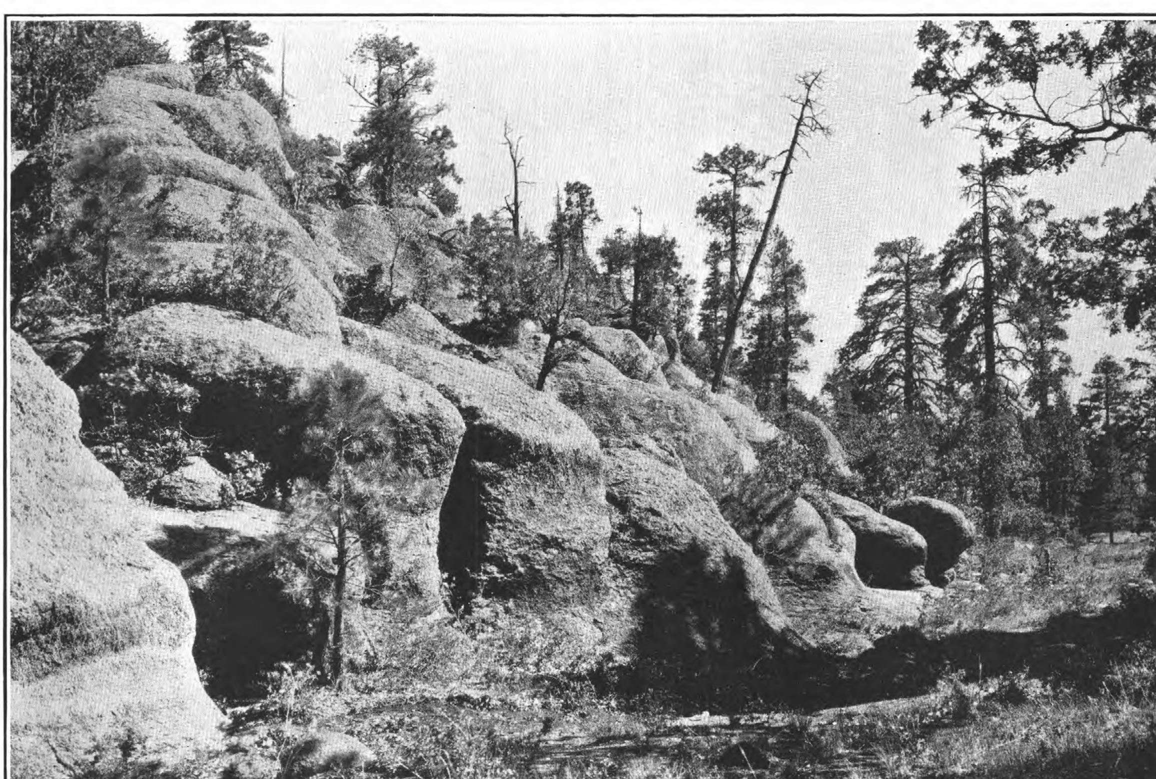
The sedimentary strata have been uplifted in a block of approximately rectangular plan and tilted to the east by the intrusion of igneous rock. The dip of the strata ranges between 30° and 60°, the average of 24 measurements being 45°. The strike of the beds is from 20° to 45° E., averaging 30°, in a direction diagonal to the sides of the block. The only exception is in the small hill on the extreme east side of the block (*b*, fig. 18), where the Kaibab limestone strikes due north; the dip at this locality, however, conforms to the average. Dips of 40° to

[1] Whipple, A. W., Report of explorations near the 35th parallel of north latitude, vol. 3, part 1: S. Ex. Doc. 78, 33d Cong., 2d sess., 1856, p. 80.



A. ELDEN MOUNTAIN FROM OBSERVATORY MESA, ON THE WEST.

Showing dome shape of central mass. The slopes are youthfully dissected, with alluvial fans at mouths of ravines.



B. STRUCTURE AND TEXTURE OF THE IGNEOUS ROCK OF ELDEN MOUNTAIN, NEAR DOYLE'S SPRING, AT NORTHWEST BASE.

Showing large scale of the joint system and the spheroidal weathering.

50° occur in the easternmost exposures, so that the line along which the strata return to their normal horizontal position must lie still farther east, where it is covered by alluvium.

The contact between the sedimentary rocks and the dacite is well exposed on the north and west sides of the block; on the south side and the eastern part of the north side it is hidden under alluvium. The Redwall limestone, which is in contact with the dacite along the entire west side and part of the north side of the block, has been metamorphosed throughout its exposed thickness of 300 feet to a pure, coarse-grained white marble. The overlying red sandstone of the Supai formation has not been noticeably affected, although it may show a slight baking, with loss of color, at the contact with the marble. A zone of breccia in places 50 feet wide, composed of fragments of dacite, limestone, and other sedimentary rocks, the whole impregnated with calcite, is situated between the sedimentary strata and the dacite on the west side of the block. The slope of the igneous rock on the north and south sides of the block is 30° E., whereas the dip of the strata averages 45°, and this difference must cause the dacite to come into contact with all the formations in the sedimentary block. This relation can not be actually observed, as the contacts are covered by alluvium.

The block has been extensively faulted both parallel to and across the strike of the beds. The thickness of the formations, as measured in the field, is about 4,000 feet. The actual thickness, however, can not greatly exceed 2,000 feet, as shown by unfaulted sections measured in the San Franciscan region and adjacent country (p. 21). The difference of 2,000 feet must represent the amount of down faulting to the west. The fact that the throw of the strike faults is to the west shows that the movement occurred after or as the result of the extrusion of the dacite from beneath the block, even though the fracturing may have been produced originally during the intrusion of the igneous rock.

The exact number and the position of the strike faults were not determined, nor were the displacements individually measured, as they occur mostly in strata of the same lithologic character. The four faults shown on cross section *A–A′* (fig. 23, p. 83) therefore indicate the general fact of the faulting rather than any definite details concerning it. Three east-west faults, parallel to the north and south sides of the block, are indicated by the offsetting of the contact between the Coconino sandstone and Kaibab limestone. The two northernmost have throws in opposite directions and have resulted in raising the middle portion of the block above the narrower portions on either side, as represented in cross section *B–B′* (fig. 23). The third fault is a continuation eastward of the southern boundary of the main part of the block. The presence of two short faults is shown in the northern part of the block by an area of Redwall limestone surrounded by Supai sandstone. The western of these two faults extends N. 30° W. from the west end of the northern east-west fault to the edge of the block; it has a throw to the west of perhaps 500 feet. A dacite dike, the only one observed in this area, occupies the fault plane and connects directly with the main dacite mass.

As the sedimentary block was raised above the general level of the country from a hinge line along its eastern side, it follows that the boundaries on its north, south, and west sides are marked by faults. The displacements on the north and south sides must increase from zero at the hinge line to a maximum at the west side of the block. The throw of the fault along the west side must lie between the maximum values of the other two faults. If the block had been tilted in an unbroken condition, this would have been about 4,500 feet; it is actually 2,000 feet less because of down faulting to the west that occurred within the block. The result of all the faulting was to cut the eastern sedimentary block into a complex of smaller parts, the exact character of which was not determined.

NORTHERN SEDIMENTARY AREA.

The northern sedimentary block is smaller in size than the eastern block and has been very much less eroded. The southeast face has retreated northward slightly from its original position and the northwest slope is scored by sharply incised ravines of youthful appearance.

The sedimentary formations exposed include only the upper 200 feet of the Coconino sandstone and 350 feet of the Kaibab limestone. Overlying the limestone, however, is a series of volcanic formations, nearly 500 feet thick, made up in ascending order as follows:

Volcanic formations overlying Kaibab limestone on Elden Mountain.

	Feet.
Basalt (eroded patches)	10
Latite (ash)	10
Latite (lava)	170
Fragmental material	300±

These will be mentioned later in discussing the age of Elden Mountain.

The sedimentary and volcanic rocks have been uplifted together and now strike N. 35° E. and dip 12° W. This strike is closely parallel to the direction of the hinge line of the block, which runs about N. 25° E. and is supposed to pass through Schulz Spring. There was no interior faulting of the block, presumably owing to the slight extent of the tilting, but the north, south, and east boundaries are marked by faults in the same manner as in the eastern block. The throw of the north and south side faults increases from zero at the hinge line to a maximum of 2,500 feet on the east side of the block.

The sedimentary rocks and the dacite of Elden Mountain are not seen in actual contact. They approach each other very closely along the east side, but the contact is covered either by talus or alluvium. The lavas of the Dry Lake Hills are in contact with the sedimentary rocks on the south side of the block.

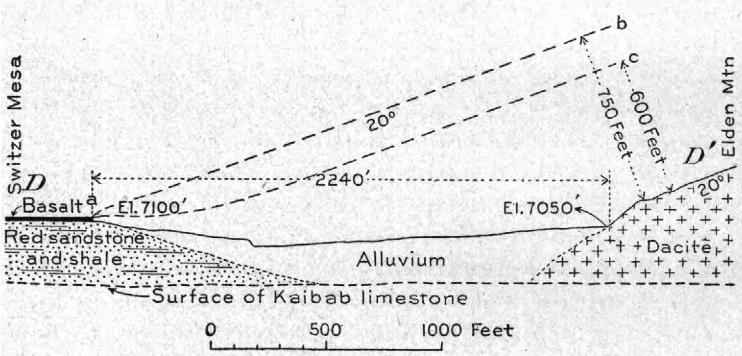


FIGURE 19.—Cross section from Switzer Mesa to west slope of Elden Mountain. For line of section see *D–D'*, figure 18.

ORIGIN OF ELDEN MOUNTAIN.

The tilted sedimentary strata on the east and north sides of the mountain and the textural and structural features of the igneous rock suggest that Elden Mountain is a laccolith whose cover has been largely removed and the uneroded remnants buried beneath the mantle of waste that encircles the base of the mountain. It can be shown, however, that the igneous rock was never covered by sedimentary strata except at the two localities on the east and north sides of the mountain, and that consequently the remainder of the mass is of extrusive origin. That is to say, Elden Mountain combines, it is believed, what may be properly called laccolithic intrusion with volcanic extrusion.

Proof that the igneous rock was not completely covered by sedimentary strata is based on three different lines of evidence. The first is derived from the structure of the mountain, the second from the extent of erosion compared with that of the large cones of the second general period of eruption, and the third from a study of the physiographic development of the mountain considered as a laccolith.

The structural evidence may be considered first by examining the relation that a cover would bear to the igneous mass at several critical localities. On the west side of the mountain the basalt-capped and horizontal beds of the Moencopie formation approach within 2,240 feet of the base of the mountain, the intervening space being covered with alluvium (fig. 19). If a cover existed at this locality the strata must have been upturned in the space between the edge of the mesa and the foot of the mountain. The mountain has a uniform slope of 20° which would also be the slope of the cover. The thickness of the cover, therefore, may be determined by drawing a line (*a–b*, fig. 19) from the edge of the mesa parallel to the slope of the mountain and measuring the perpendicular distance between it and the slope. The thickness of the cover, as thus obtained, is 750 feet. It would seem more reasonable to consider that the tilting did not occur abruptly at the edge of the mesa, but took place more gradually until the maximum slope of 20° was reached. This restoration is shown by the line *a–c*, and the thickness of the cover indicated is 600 feet. Such a figure is so completely at variance with all known observations regarding the thickness of laccolithic covers as to justify the conclusion that the igneous rock of Elden Mountain was never mantled by sedimentary strata at this locality.

A second locality that may be examined is at the eastern corner of the northern sedimentary block, where there is exposed a thickness of 1,000 feet of strata, the upper half of which is volcanic in origin (fig. 20). The horizon of intrusion is placed in the upper part of the Redwall limestone to correspond to the horizon in the eastern sedimentary block (p. 82). The distance between the lowest exposure of sedimentary rock (at *a*, fig. 20) and the dacite on the opposite side of the ravine at this point is but a few hundeed feet. If the plane of intrusion is correctly placed in the Redwall limestone, it is evidently impossible that the 1,400 feet of strata below the lowest exposure at *a* should be upturned on the flank of the dacite mass. A cover may be assigned to the igneous rock only by assuming that the intrusion took place at a higher stratigraphic horizon under the northern block than under the eastern block. In this case it could be but little lower than the lowest exposure at *a*, and this would place it in the Coconino sandstone. The thickness of the cover would thus be not over 1,000 feet, or so thin that doubt is at once felt as to its reality. The most probable assumption as to conditions at this locality, then, shows the impossibility of a cover over the igneous rock; a less likely assumption indicates the existence of a cover as very improbable.

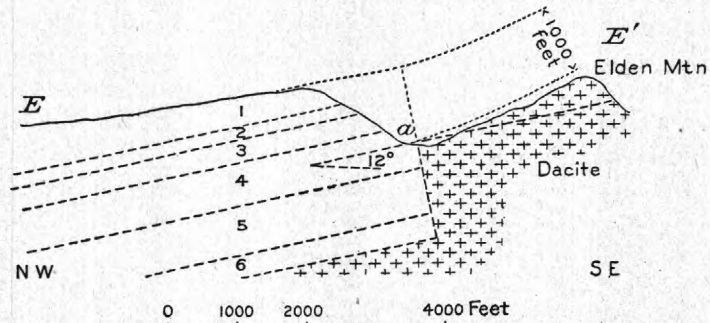


FIGURE 20.—Cross section through north slope of Elden Mountain. 1 and 2, Volcanic breccia and lava; 3, Kaibab limestone; 4, Coconino sandstone; 5, Supai formation; 6, Redwall limestone. For line of section see *E–E′*, figure 18.

Consideration of a third locality, including the slope from the main summit of the mountain eastward through the southern part of the sedimentary block (fig. 21), is also instructive. The small revet hill (*f*, fig. 18) is composed of Kaibab limestone capped by basalt, which definitely fixes the original horizon of the upper surface of the block. The plane of intrusion is in the Redwall limestone. The strata strike N. 40° E. and dip 4° E. As the section is drawn diagonally to the strike, the dip appears to be only 25°. The contact between the dacite and sedimentary rocks is covered by alluvium, but the restoration shows that it is close to the surface at *a* (fig. 21). If it were supposed that the strata once extended unbrokenly over the dacite, the thickness of the cover would be equal to the distance *a–x*, or 400 feet. Or, by the assumption of a fault along the west side of the block *d*, it might be supposed that the block *c*, of the same thickness as *d*, was raised to the position *c′*. The two would be in contact from *a* to *x*, a distance of 400 feet, and the western block would rise 1,500 feet (*x–y*) above the eastern one. Both suppositions lead to such unusual results that they may be dismissed as impossible. The conclusion is reached that the igneous rock was never covered by sedimentary strata and that it is, consequently, an extrusive lava whose farther extension eastward was checked by the tilted strata of the block *d*.

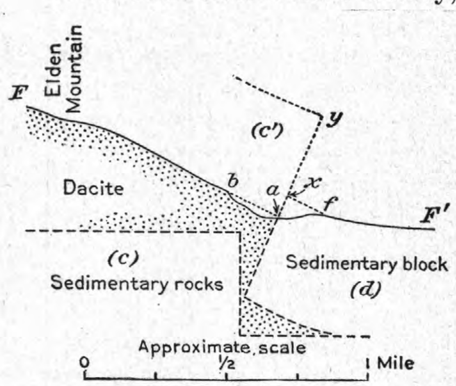


FIGURE 21.—Cross section through east slope of Elden Mountain. For line of section see *F–F′*, figure 18.

Further proof, showing the improbability of the existence of any cover over the igneous rock, may be obtained from the relation between the igneous and sedimentary rocks on the north and south sides of the eastern sedimentary block.

The extrusive nature of the main mass of Elden Mountain may be shown by comparing the relative amounts of erosion undergone by the mountain and the large volcanoes. Elden Mountain, as will appear later, is of the same age as the large cones and consequently should be eroded to the same proportionate extent—that is, it should have lost about 10 per cent of its volume. If the mountain is supposed to be a denuded laccolith of normal type, then it must have lost fully 50 per cent of its volume in reaching its present condition. The discrepancy shows the incorrectness of the assumption of a laccolithic origin for the entire mountain. When the igneous rock is considered as effusive, it is seen that the amount of erosion the mountain has experienced, as judged by the character of the ravines and extent of the waste fans, agrees closely with that of the large cones.

The physiographic argument is based on a hypothetical consideration of the manner in which the erosion of the mountain, considered as a laccolith, might proceed. A cover of 2,000 feet of strata, the thickness of the beds in the eastern block, is assumed. The question to be answered is, Could such a cover be removed so that no vestige of it would remain on the slopes or about the base of the mountain?—that is, Could the igneous mass be left in its present condition, for example, on the west side of the mountain?

The initial drainage lines upon the domed and presumably somewhat shattered cover of the laccolith would be radial. Sharply incised ravines would be cut in the steeply sloping (20°–30°) and resistant Kaibab limestone and Coconino sandstone. As these formations were removed from the upper part of the dome, the sandstone of the Supai formation would be exposed. The strata composing this formation are relatively soft, and erosion would proceed more rapidly, the removal of the overlying beds being accelerated by undermining. Eventually the sandstone of the Supai would be eroded from the upper slopes and the Redwall limestone would become the surface rock. At about this stage the Kaibab limestone and Coconino sandstone would form a series of interravine revet hills on the slopes at some elevation probably nearer the foot than the summit of the mountain, as is actually the case in the eastern sedimentary block. The Redwall limestone could not be stripped from the igneous rock, for the two are nearly equally resistant. In order to have it completely removed and the revet hills on the lower slopes beveled off and buried beneath the waste-covered base of the mountain, it would be necessary for erosion to proceed until the igneous core was much denuded and maturely dissected. None of these features, however, are present. (See Pl. X, *A*, p. 76.) The topography is of a distinctly youthful type; the slopes are cut by sharply incised ravines and large areas of interravine slope are essentially uneroded. These features can not be considered as developed during a new cycle of erosion upon the maturely dissected mass of the earlier cycle. It is necessary to conclude, therefore, that the erosion of the mass is not far advanced, and consequently that sedimentary strata never overlay the igneous rock except at the two localities where they now do so.

The correctness of this reasoning is supported by the observed conditions on the west side of the mountain, where Switzer Mesa approaches nearest its base. It will be recalled that the strata must have been upturned at the very eastern edge of the mesa if a cover existed at this locality. It would be expected, then, that the surface of the mesa should be cut by ravines representing the lower courses of those developed on the cover of the laccolith, or perhaps be thickly mantled with waste from the mountain. But on the contrary the mesa is uncut by any such ravines and its surface is covered only by basalt erupted before the formation of the mountain.

Another significant point is the absence of dikes in the upturned sedimentary strata on the north and east sides of the mountain. None were observed in the northern block and but one, located on a fault, in the eastern block. The absence of dikes in the eastern block, which is so thoroughly faulted, would seem to indicate that the igneous rock was able to escape by a much easier passage than was offered by the fault planes. That this was no doubt true will be shown in a later paragraph.

All lines of evidence, therefore, point to the same conclusion, namely, that the igneous rock of Elden Mountain was never overlain by sedimentary strata except at the localities on the north and east sides. That is to say, the igneous rock under the sedimentary blocks is intrusive and the remainder is extrusive.

The dome-shaped form of the mountain is not due, then, to laccolithic intrusion, but to the high degree of viscosity of the erupted lava. The rate of extrusion was greater than the rate of flow. As the result craterless domes with steep convex slopes were formed whose height was approximately equal to one-quarter the diameter of their base. A consideration of the form of the extruded mass with respect to the outlets creates an impression that the eruptions were few but of large volume.

Had it not been for the tilted sedimentary strata on the slopes of the mountain and definite peculiarities in the texture and structure of the igneous rock, an extrusive origin might well have been assigned to Elden Mountain on the basis of topographic form alone. The "dome" type of eruption is well known and is present at other localities in the region, for example, at the Dry Lake Hills and Bill Williams secondary cones.[1] The type is apparently not uncommon in the Basin Range country of Nevada, where, according to Gilbert,[2] the "trachyte" and rhyolite are—

> characterized by what have been called massive eruptions; that is, by viscous eruptions of great volume, the lava of which instead of flowing off in coulees or building cones by slow accumulation of congealed streams, has, by single or few issues, formed bosses, often of great thickness and divided by few or no surfaces of bedding.

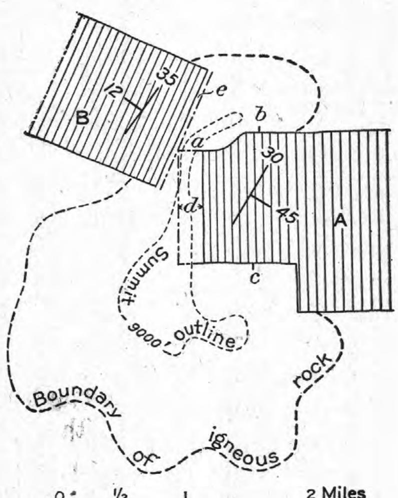


FIGURE 22.—Plan of Elden Mountain, showing tilted sedimentary blocks (A, B) and area of igneous rock.

MODE OF FORMATION.

It is evident that the initial vent or fissure along which the igneous rock rose from below was situated between the two sedimentary blocks near the point where they came into contact (*a*, fig. 22). It was probably for the most part under the eastern block, because of the greater tilt of that block. The location of the only area of breccia between the two blocks is believed to signify explosive phases of activity, such as are commonly associated with the opening of a volcanic vent. The igneous rock, however, did not immediately reach the surface at this point, but instead was intruded into the Redwall limestone at a depth of about 2,000 feet below the surface of the country. It has been assumed that the intrusion occurred 400 feet below the top of the formation; the complete metamorphism of the limestone to marble and the wide zone of brecciation between the dacite and the west side of the sedimentary block have suggested the location of the horizon of intrusion at this level. The exact horizon can not be determined, but it would be somewhere in the Redwall limestone, for very probably below this formation occur the greatly contorted pre-Cambrian rocks. It may well be supposed that the initial intrusion tended to give rise to a laccolith and that it was of irregular shape, as the igneous rock was forced into a heavy-bedded and resistant formation. In the absence of any data on this point, however, the intruded mass is represented on the cross sections simply as regular in form. If there was such an initial doming, evidence of it is not visible; either it did not reach the surface or it has been hidden by the later eruptions. No evidence of it is to be seen in the sedimentary outcrops about the mountain.

The sedimentary rocks, instead of being raised as a symmetrical dome by the intrusion were broken out sharply from the crust and tilted up in two distinct blocks of rectangular

[1] This origin was suggested to the writer by Mr. G. K. Gilbert in a personal communication, as follows: "Another matter would be the investigation of an igneous mass seen at the southeastern base of San Francisco Mountain, the form of which suggests that it is an enormous superficia bleb, or exuded drop, too viscous at the time of its extrusion to spread out under its own weight."

[2] Gilbert, G. K., U. S. Geog. Surveys W. 100th Mer., vol. 3, 1875, p. 127.

plan (A and B, fig. 22). The rectangular plan of the northern block is the more evident. The exact outline of the eastern block is uncertain because the boundaries are largely covered by alluvial deposits; its rectangular plan is based on that of the northern block. The strike of the strata in the two blocks is practically the same, N. 30° E. and N. 35° E, but the dips are in opposite directions, thus fixing the point of uplift at the junction of the blocks (*a*, fig. 22). The eastern block was tilted much more than the northern one, the dip of the beds averaging 45° in the former as compared with 12° in the latter. As the blocks were revolved in opposite directions, an open space must have remained between them which was occupied by the igneous rock in contact with the air. As already noted, a breccia occurs in part of this area, and the evidence shows that it must be of extrusive rather than intrusive origin. The liquid dacite, on account of its viscosity, did not rise above the tops of the blocks, for had it done so some evidence in the form of flows would certainly be found on the surface of the northern block. Although the strata were not continuous between the two blocks, it seems allowable to speak of this particular portion of Elden Mountain as a laccolith. It is represented with approximate correctness by section A–A′ (fig. 23) at right angles to the strike of the strata in the two blocks. As previously stated, the number of faults and their individual throws can not be exactly determined. Only the total throw, with its direction, is known.

The igneous rock could escape and form effusive masses because the bottom of the eastern sedimentary block on its west side was raised well above the surface of the surrounding country. The present elevation of the surface of the plateau on which the dacite rests is 6,800 feet, whereas the bottom of the west side of the block lies between 8,000 and 8,500 feet. On this side, then, there was an opening 1,500 feet high and 4,800 feet long (the length of the block) through which the igneous rock could escape. Vertical triangular openings also existed on the north and south sides of the block. They extended eastward from its west side at the points (*b* and *c*, fig. 22) where the eastward-dipping bottom of the block reached the surface of the country. On account of the tilted position of the block the bottom of the west side would stand about 1,000 feet east (*d*, fig. 22) of the corresponding side of the depression formed by the uplifting of the block. This would increase the height of the opening some 300 feet, making it 1,800 feet. The total area of the openings on the north, south, and west sides of the eastern sedimentary block would thus be approximately half a square mile, which is equal to the area of a circle 4,000 feet in diameter. The opening was therefore much larger in size than any of the craters of the large volcanoes. The fact that so little lava escaped from so large an opening must have been due to the high degree of viscosity of the erupted rock.

The disposition of the dacite about the ends of the northern block shows that very little or no outflow occurred from beneath that block. The explanation of this is that, the horizon of intrusion being in the Redwall limestone, the tilt of the block (12°) was not sufficient to raise the bottom above the level of the surrounding country. There were therefore no vertical openings on the north, south, and east sides and only a narrow horizontal one (*e*, fig. 22) on the east side through which the igneous rock could escape. If, as previously assumed (p. 79), in order to give the dacite a cover at this locality, the horizon of intrusion had been situated in the Coconino sandstone, then large openings would have existed and so great a volume of lava would have been erupted from beneath the block that it could not escape detection.

It may be said, therefore, that the dacite was extruded almost entirely from beneath the eastern sedimentary block and that the openings through which it escaped had an area of about half a square mile. If there is more than 400 feet of Redwall limestone in the block, the size of the opening would be decreased. But even if the entire thickness of the formation (1,000 feet) were included, an opening 0.3 square mile would still remain. This is equal to the area of a circle 3,000 feet in diameter, and by comparison with the craters of the large cones would be of ample size to permit the escape of the dacite.

It will be seen from figure 22 that the lava was extruded in much greater volume south of the two sedimentary blocks than north of them and that the line of separation between the two areas is located where the blocks are closest together (*a*, fig. 22). This unequal distribution of the lava naturally followed from the fact that the area of the opening through which it could escape was greater south of this locality than north of it. It is estimated that the ratio of the size of the openings north and south of *a* is 1 : 4.5, whereas the ratio of the corresponding volumes of lava is 1 : 8—that is, the southern orifice having 4.5 times the area of the northern one, permitted the escape of 8 times the volume of lava. The difference is due to the greater ease with which the highly viscous lava flowed through the larger opening. The result agrees with observations which show that the discharge of fluids from small orifices is relatively less

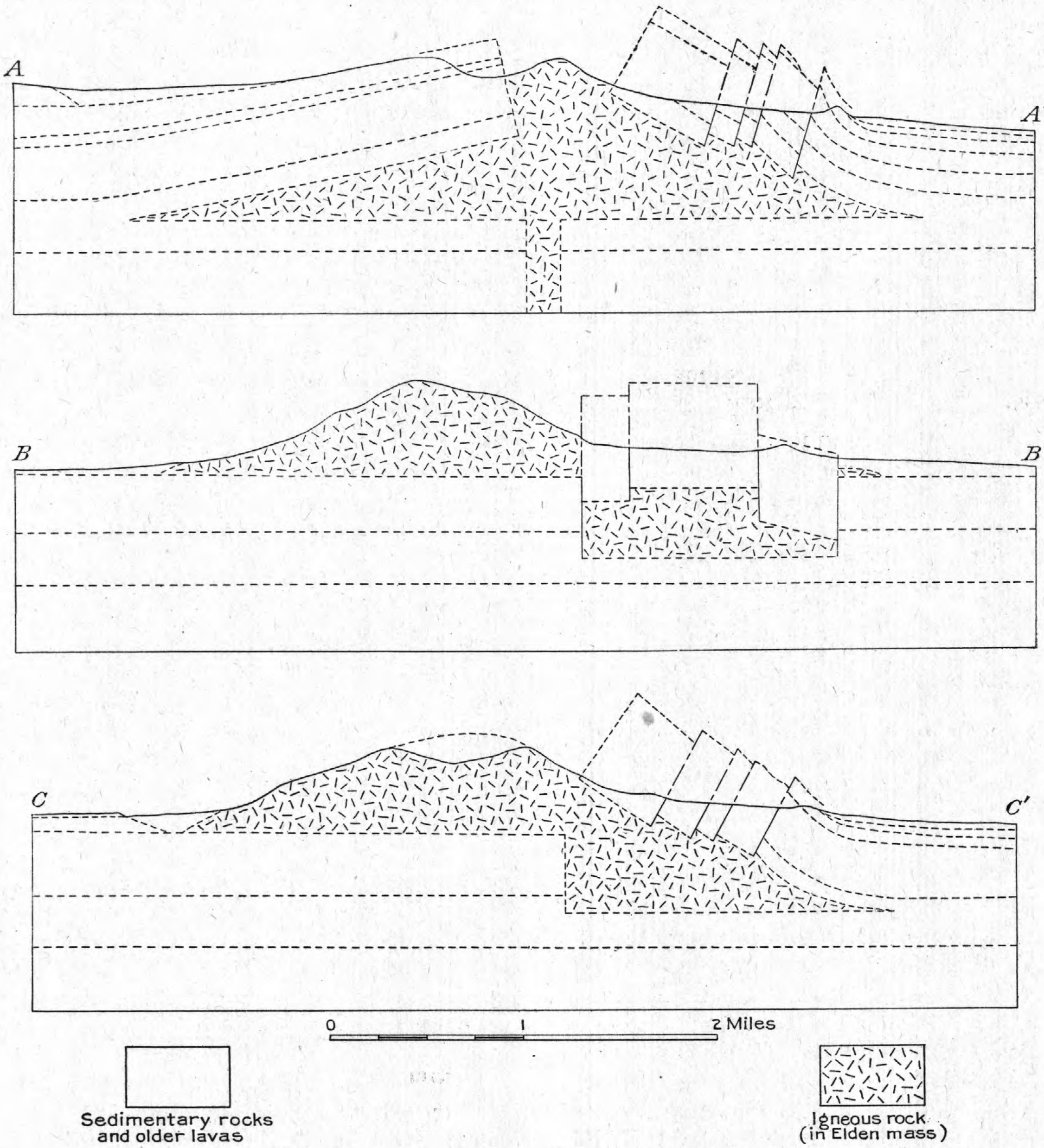


FIGURE 23.—Geologic cross sections of Elden Mountain. For lines of sections see figure 18.

than that from large ones because of the more rapid increase in friction as the size of the orifice decreases.

The greater part of the extruded rock, as outlined by the 9,000-foot contour (fig. 22), lies southwest of the eastern sedimentary block. This indicates either that the force of expulsion was toward the southwest or that a relatively larger opening existed at this locality, or perhaps both. The minimum observed dip of 30° is in the Redwall limestone at the northwest corner of the block, but dips of 50° to 60°—the maximum observed—occur in the outcrops nearest the southwest corner. It is evident that these steeper dips in the southwestern part of the block are necessary in order that the height of the opening at this corner should be as great as at the northwest corner, because the strike of the beds is diagonal to the boundaries of the block. The same result might have been obtained if the intrusion broke into higher stratigraphic horizons in the southwestern part of the block. A satisfactory conclusion can not be reached, because lack of knowledge in regard to the faulting prevents the accurate restoration of the block.

The laccolithic phase of Elden Mountain is represented with some accuracy by section A–A′ (fig. 23). The intrusive-extrusive phases are shown in sections B–B′ and C–C′, which are diagrammatic. They have been simplified, particularly with respect to the faulting. Section B–B′ passes through the summit of the mountain and the eastern block, on a line parallel to the strike of the strata except in the northern fault block. As it cuts the main block east of the points at which the strata rise above the level of the surrounding country, the intrusive and extrusive parts of the igneous rock appear disconnected. Only the east-west faults are shown and the fault planes are drawn vertically to indicate that no lateral expansion of the block has occurred. This interpretation is based on the absence of igneous dikes notwithstanding the much-faulted condition of the block. If the fault planes had the slopes usually required by the size and position of the individual fault blocks, there would have been, most probably, a considerable expansion of the block and an intrusion of dikes along the fault planes. Section C–C′ passes through the southwest corner of the middle fault block in a northeast-southwest direction. It is therefore diagonal both to the strike of the beds and to the fault planes. This fact makes an accurate restoration very difficult because of incomplete knowledge concerning the nature of the faulting. The section will give some idea, however, of the relative size of the intruded and extruded masses of igneous rock and the manner in which the lava is supposed to have escaped from beneath the block.

AGE OF ELDEN MOUNTAIN.

Outcrops of basalt occur in the eastern sedimentary block on the east slopes of the small hills marked *a* and *b* in figure 18 (p. 75). The lava rests on the Kaibab limestone and was upturned with it. It therefore antedates the formation of the mountain and belongs to the first general period of eruption of the region. Resting upon the Kaibab limestone in the northern block, and upturned with it, is a basalt overlain by a latite, both as ash and lava, which in turn is covered by a volcanic breccia. The basalt is identical with that on the eastern block and belongs to the first general period of eruption. The latite originated at San Francisco Mountain during its first stage of activity, and the overlying breccia is assigned to the same stage by the restoration made on section *A–A′* of San Francisco Mountain (Pl. VI, p. 40). The time of the formation of the mountain is thus fixed by the upturned lavas capping the sedimentary blocks as having been after the first stage of eruption in San Francisco Mountain. The dacite of Elden Mountain is identical in chemical and mineral composition with the dacite of San Francisco Mountain, as well as mineralogically the same as the lavas of Schulz Peak and the Dry Lake Hills. For this reason, and because no lavas younger than the latite are upturned on the flanks of the mountain, it is believed that the dacite of Elden Mountain may be correlated directly with the dacite of San Francisco Mountain. The formation of Elden Mountain was thus contemporaneous with the second stage of activity in San Francisco Mountain. It will be recalled that the dacite of the Dry Lake Hills is considered as having been erupted during this same stage of activity but after the dacite of Elden Mountain. Consequently, the length of time necessary for the complete formation of Elden Mountain was somewhat less than the whole interval represented by the second stage of activity of San Francisco Mountain.

SUMMARY.

Elden Mountain combines intrusive and extrusive phases of igneous activity as contemporaneous phenomena in the same geologic unit. The intrusive or laccolithic portion lies beneath two tilted sedimentary blocks of rectangular plan, about 2,000 feet thick, situated on the north and east sides of the mountain. The extrusive portion rests upon the level surface of the plateau, in part to the north but principally to the south and west of the sedimentary blocks. The highly viscous condition of the igneous rock and the resistant character of the limestone into which it was initially intruded presumably prevented the development of a normal laccolith.

The fissure or vent along which the igneous rock rose was located close to the point of contact of the two sedimentary blocks—more largely, however, under the eastern block, which was tilted on the average 45° and much faulted, whereas the northern block was tilted but 12° and remained unfaulted. The intrusion occurred in the Redwall limestone at a horizon estimated at 400 feet below the top of the formation.

The uplift of the northern block was not sufficient to permit the escape of the intruded rock upon the surface of the country. The eastern block, on the contrary, was raised so that there was an opening of about half a square mile between the lower edge of the block and the surface of the plateau. Through this opening practically all the lava was extruded. The position of the eastern block was rendered unstable by the outflow of the lava from beneath it, and as a result faults developed both diagonal and parallel to the strike of the strata. The opening under the eastern block was larger south of the point of contact of the two blocks than north of it, and in consequence the greater portion of the lava was erupted on that side.

The lava composing the mountain is a dacite. The textural and structural features of the rock and its form in mass indicate that it possessed so high a degree of viscosity that it was unable to spread out as rapidly as it was erupted from the orifice. Consequently it solidified in huge dome-shaped piles.

Elden Mountain is known to have been formed after the eruption of the latite of the first stage of activity of San Francisco Mountain, because that lava is upturned with the sedimentary strata on the flanks of the mountain. It was, however, probably formed before the dacite eruptions of the Dry Lake Hills. In view of the identity of the dacite of Elden Mountain in chemical and mineralogic composition with the pyroxene dacite of San Francisco Mountain the formation of Elden Mountain is fixed as occurring during the second stage of eruption of San Francisco Mountain.

SLATE MOUNTAIN.

Slate Mountain, 6 miles north of Kendrick Peak, rises 1,000 feet above the surrounding country and has a basal area of 1 square mile. The mass has been somewhat eroded, and alluvial fans are prominent on the north side.

The hill is almost entirely composed of a compact rhyolite which bears a close resemblance both in hand specimens and in thin sections to the supposed core rock of Sitgreaves Peak and is also very similar to the porphyry of Marble Hill. The rock is fairly uniform in texture. At one point, in a small detached knob S. 20° W. of the summit, at the limit of the igneous rock in that direction, a breccia composed entirely of rhyolite is developed and the unbrecciated rock is cut by a system of small cracks that appear to have resulted from stretching when the rock was in a highly viscous condition.

Sedimentary strata having an average quaquaversal dip of 25° lie about the foot of the hill between N. 60° E. and S. 20° E. (by way of east) from the summit. They either rest upon the lower main slopes or through erosion form small detached knobs. The beds immediately above the igneous rock are white sandstones, in places cross bedded, overlain by limestones. Their identity was not definitely determined. On the basis of lithologic similarity it seems probable that they should be assigned to the cross-bedded Coconino sandstone and the cherty Kaibab limestone. Otherwise the limestone would have to be referred to the Redwall and the sandstone considered an intercalation. The thickness of the first-mentioned series would be about 800 feet, and that of the second over 2,000 feet.

If the strata are equivalent to the Coconino sandstone and the Kaibab limestone, it is certain that Slate Mountain is similar in character to Elden Mountain—that is, partly laccolithic, partly volcanic in origin, and probably contemporaneous with Marble Hill. If, on the contrary, they belong to the Redwall limestone, the hill is entirely laccolithic. It may be noted that in this case Marble Hill and Slate Mountain would have the same thickness of cover, but that the latter would be in a very much more eroded condition. This would set the time of intrusion at a considerably earlier date than that of Marble Hill. A guess based simply on the character of the igneous rock and the extent of the alluvial mantle favors the semi-laccolithic origin of the mass.

From field evidence it can only be said that Slate Mountain was formed previous to the basalt eruptions of the third general period. No lavas were observed upturned with the sedimentary rocks on the flanks of the hill; it is probable that none will be found, unless it is the basalt of the first general period, as Slate Mountain lies outside of the area covered by the lavas of either San Francisco Mountain or Kendrick Peak.

SUMMARY OF SECOND GENERAL PERIOD OF ERUPTION.

Six large cones and a somewhat greater number of small ones belong to the second period of eruption, and also one laccolithic and two semilaccolithic masses which were formed contemporaneously with the volcanoes. The lavas range in composition from andesites to rhyolites. The total volume of the erupted lava is calculated to be 56 cubic miles.

All the large cones except Sitgreaves Peak are formed of two or more lavas of different composition. The small cones, as well as the laccolithic and semilaccolithic masses, are composed of a single lava. Each of the composite cones has its own particular sequence of lavas which differs from those of the other cones. This is shown by the following table:

Composition and sequence of lavas of cones of second period.

	1	2	3	4	5
San Francisco Mountain	Latite	Pyroxene dacite	Hornblende dacite	Rhyolite	Andesite.
Kendrick Peak	Rhyolite	do	Hypersthene dacite	Andesite	
O'Leary Peak	do	Dacite			
Bill Williams Mountain	Andesite	do			
Mormon Mountain	Latite	do			
Sitgreaves Peak	Rhyolite				
Elden Mountain	Dacite				
Dry Lake Hills	do				
Observatory Mesa	Latite				
Sugarloaf Hill	Rhyolite				
Marble Hill	Granite porphyry				
Slate Mountain	Rhyolite				

The table shows that the eruptive phenomena of the period as a whole are rather complex. However, the serial characters show that the lavas are all closely related. Space does not permit these subjects to be discussed at this point; they are treated in detail in Chapter VI.

San Francisco Mountain, Kendrick Peak, and Sitgreaves Peak are distinctly symmetrical in form, because the eruptions were predominantly from central vents. Bill Williams Mountain, O'Leary Peak, and Mormon Mountain are more irregular in shape, as there was some dispersion of the main vents of these cones. Minor lateral vents are found at all the above-named volcanoes. The cones in general are composed of lava flows; fragmental material in large amounts occurs only at San Francisco and Bill Williams mountains and represents the initial stage of activity.

The cones have been only slightly eroded since they became extinct, as they have lost but 8 per cent of their original volume. The upper slopes are cut by sharply incised ravines. The lower slopes are extensively mantled by coalescing alluvial fans which head well up on the slopes of the cones. It is estimated that three-quarters of the material eroded from San Francisco Mountain has been deposited on the slopes or about the base of the cone. These fans with maximum surface slopes of 10° were formed at a time when the rate of disintegration much exceeded that of transportation. This condition is now reversed and the eroded waste is being redeposited at lower and flatter slopes. In general, erosion has lowered the summits of the cones without greatly changing the slopes below. There are extensive areas of essentially uneroded interravine slopes, which show that the cones are in a youthful stage of dissection.

The original heights and volumes and the extent to which the large cones have been eroded are given in the following table:

Original heights, volumes, and extent of erosion of large cones.

	Original height, in feet.	Volume, in cubic miles.	Summit lowered on average, in feet.	Percentage of cone eroded.
San Francisco Mountain	8,800	38	3,000	8
Kendrick Peak	4,800	6.4	1,000	8
Bill Williams Mountain	3,200	3	1,300	9
O'Leary Peak	3,500	2.1	700	....
Sitgreaves Peak	3,500	3	1,000	7
Mormon Mountain	2,500 (?)	2 (?)	....	....

The lavas of San Francisco Mountain overlie the basalt of the first general period on the flanks of Elden Mountain and Marble Hill. The lavas of all the large cones underlie a basalt which observations at other localities show is younger than that of the first period. They are thus intermediate between the two basalts and are grouped together in a separate period because of their intimate eruptive relationship and similar mode of occurrence and because the cones they built have been eroded in corresponding degree.

THIRD GENERAL PERIOD OF ERUPTION.

To the third and last general period of volcanic activity in the San Franciscan field belong about 200 basalt cones and 20 cubic miles of lava, which cover an area of 1,200 square miles. The cones are distributed more or less uniformly over the entire area, in striking contrast to the highly localized nature of the eruptions of the preceding period. (See fig. 24.) They are, however, rather more numerous in the northeastern part of the field and are especially abundant in the district east of San Francisco Mountain known locally as the Black Hills. In size and appearance the cones resemble those of the first general period of eruption, but on the whole they are better preserved and a larger proportion of them are composed of cinders.

The lava is a typical basalt almost identical in chemical composition with that of the first period. It has a very fine texture and phenocrysts are rarely visible in it. It occurs for the most part as flows, but fragmental material in the form of cinders is also common in the Black Hills. As compared with the basalt of the first period the lava tends to form thicker and rougher flows of smaller extent, which points toward a greater viscosity. The basalts of the first and third periods are, however, in many places so closely alike that it is very difficult if not impossible to distinguish between them either in the field or in the laboratory. On this account and owing to the reconnaissance nature of the field work, the boundary between the two lavas, especially in the western part of the region, has been only approximately located. A closer study may show that part of the lava mapped as basalt of the third period belongs to the first period.

The basalt of the third period overlies the lavas of the second period at many points around the foot slopes of the large volcanoes. The relationship is best seen at Kendrick Peak, where the eruptions took place well up on the slopes of the main cone (fig. 9, p. 53). Likewise it overlies the basalt of the first period, as may be clearly seen along the boundary of the volcanic field in the Little Colorado Valley and at Cedar Ranch (Pl. III, p. 20). It is therefore the youngest lava of the volcanic field. At the time of the eruptions the region had essentially the same attitude as to-day. For example, at the localities just mentioned flows overran the edges of mesas from 200 to 700 feet in height when they had very nearly their present form. At Grand Falls, also, little work has been done by the river in establishing a new course since the old one was obstructed by a lava flow of the third period. Although these conditions indicate that the eruptions of this period are geologically recent, a small number of the cones and the flows are still younger and may indeed belong to historic times. To this very recent stage of activity are assigned the cone and lava flow situated 10 miles northeast of Cedar Ranch,[1]

[1] Johnson, D. W., A recent volcano in the San Francisco Mountain region, Ariz.: Bull. Geog. Soc. Philadelphia, vol. 5, No. 3, 1907.

the cone and flow 4 miles northeast of O'Leary Peak, and several flows and conelets near Sunset Peak. The small isolated flow at Black Falls is provisionally placed in this stage because of the extreme freshness of the lava, and possibly a very perfect cinder cone a short distance west of the cone and flow 10 miles northeast of Cedar Ranch should be included.

Basalts equivalent in age to those of the third period of eruption in the San Franciscan volcanic field occur at many localities in the southern plateau country. The nearest group, locally known as the Dog Knobs, lies just north of the San Franciscan region and should properly be included in it. There are large areas of recent basalt on the Black and Mogollon mesas, where some of the flows overran the edge of the plateau and reached the lower country to the south. The basalts of the Uinkaret Plateau may be noted in particular, and the description of that region given by Dutton[1] may be applied unaltered to the basalts of the San Franciscan field.

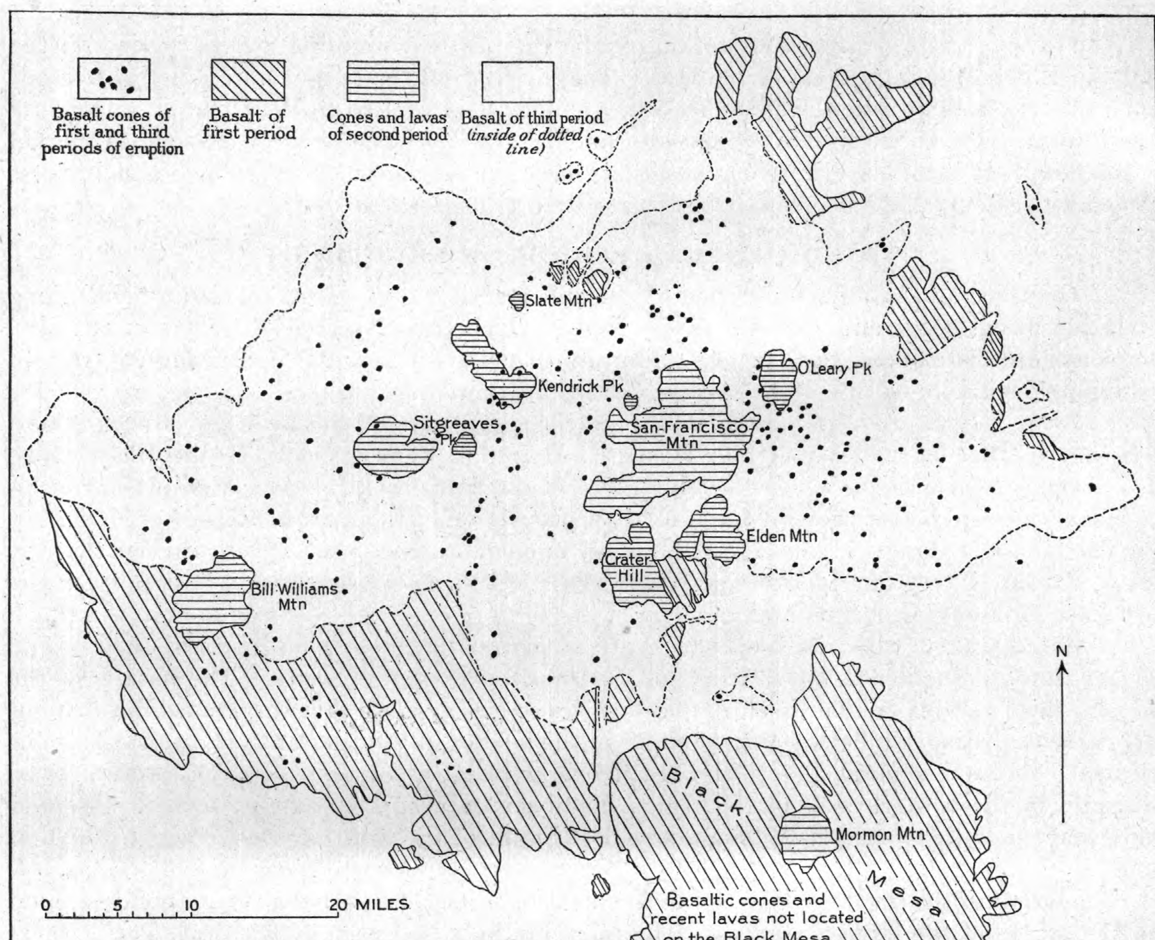
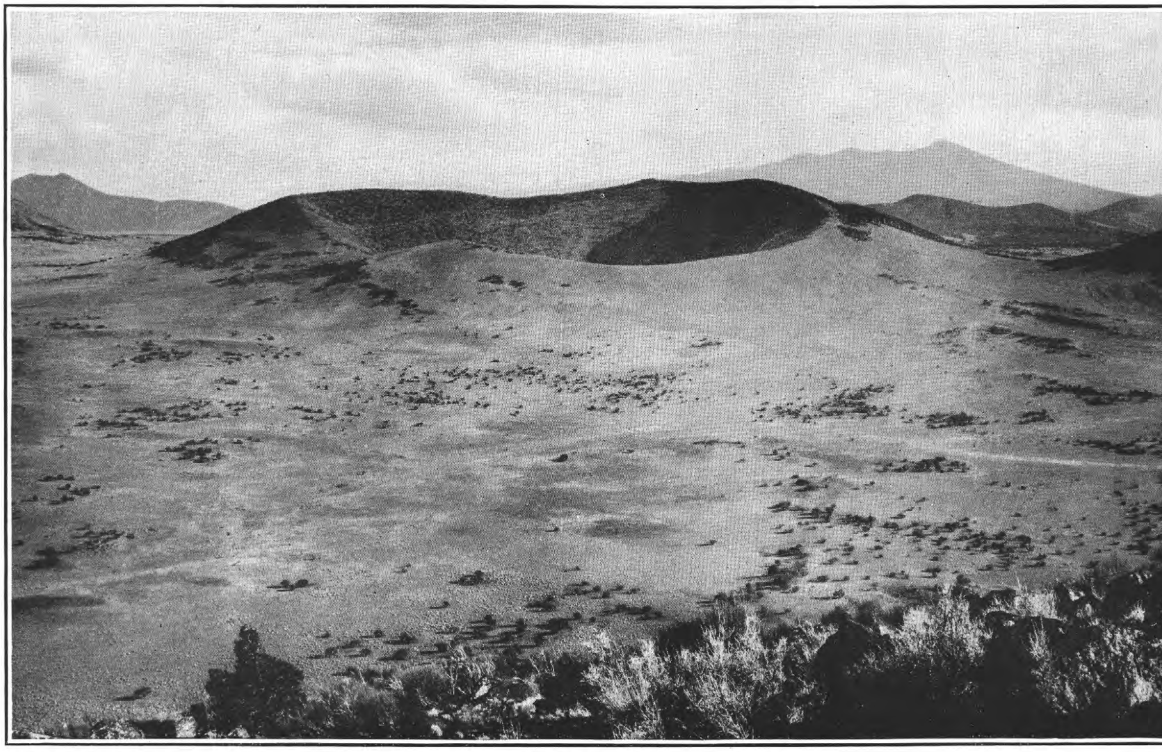


FIGURE 24.—Map of San Franciscan volcanic field, showing distribution of cones.

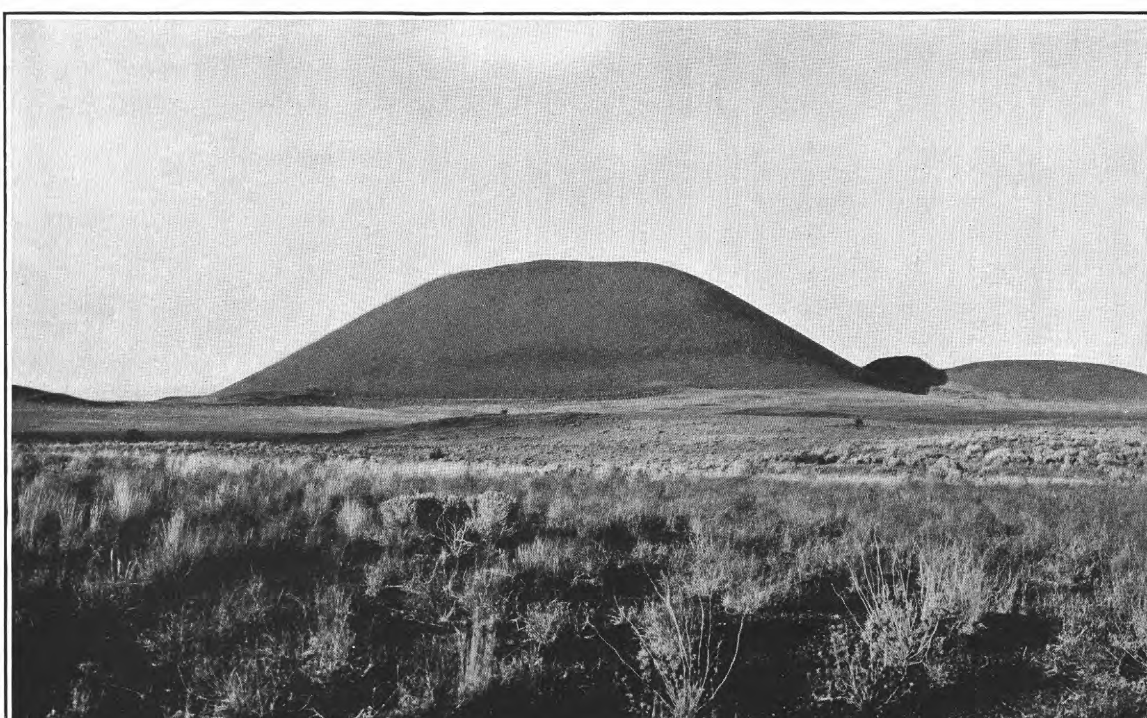
The remainder of this section is devoted to brief descriptions of individual cones and flows of the third period of eruption. In connection with the accompanying illustrations they will give a fair idea of the character of the volcanic phenomena of this period.

The cone shown in Plate XI, *A*, is situated next south of the very recent cone and flow on the northeast edge of the field. The structure is composite, the lower two-thirds of the crater walls being formed of ash, the upper third of lava. The crater is much larger than the average, and it is inferred from the uniform outward dip of the lava about the rim that it has been enlarged by a down-slipping of the walls. On the floor of the crater, though not visible in the picture, is a secondary conelet, not over 50 feet high, composed entirely of ash.

[1] Dutton, C. E., Tertiary history of the Grand Canyon district: Mon. U. S. Geol. Survey, vol. 2, 1882, pp. 104–112.

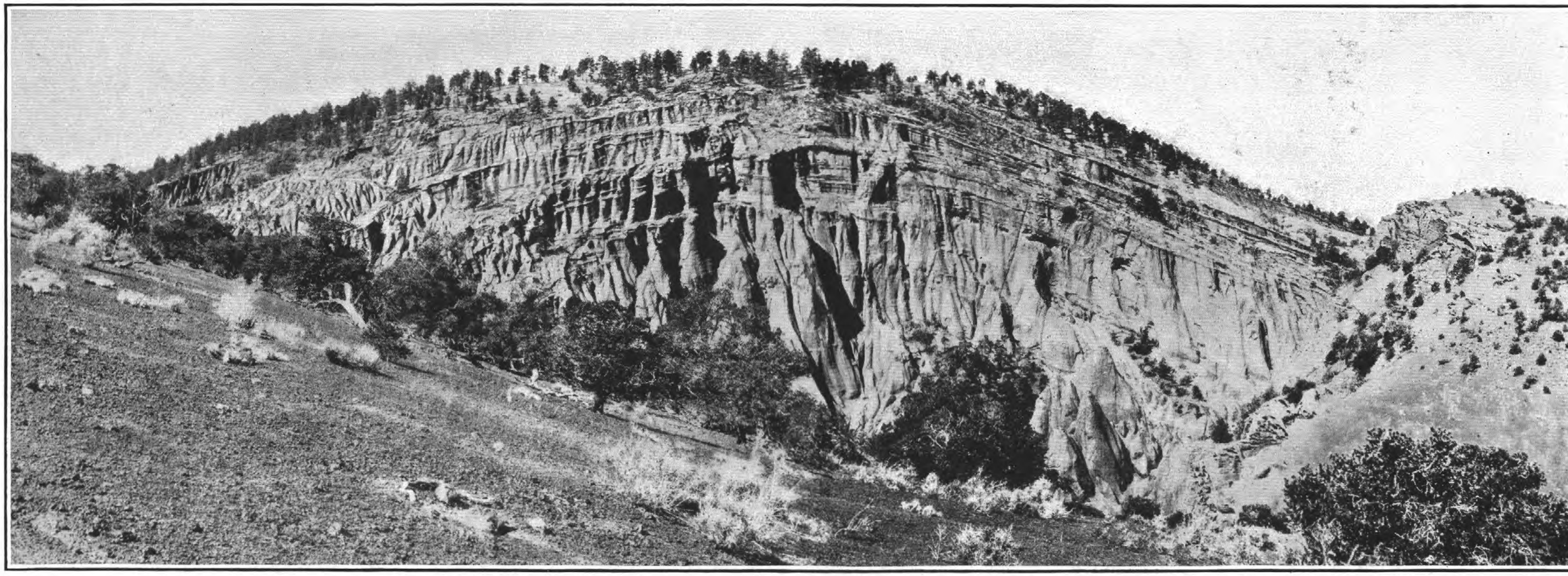


A. ON NORTHEAST EDGE OF FIELD.

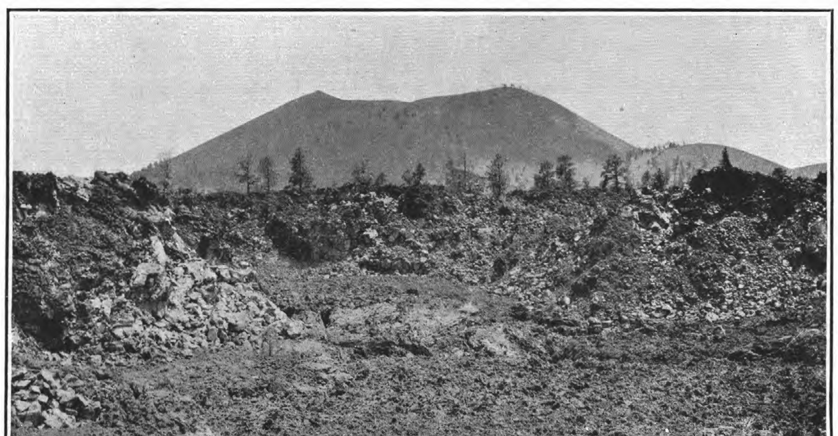


B. ON SOUTHEAST EDGE OF FIELD.

BASALT CONES BELONGING TO THIRD PERIOD OF ERUPTION.

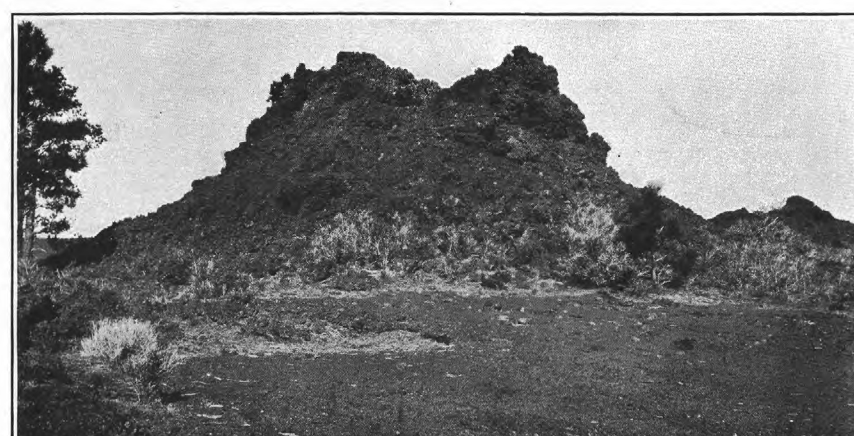


A. DISSECTED ASH CONE OF RED MOUNTAIN AT HEAD OF HULL WASH.



B. SUNSET PEAK.

Basalt cone of the third period. Depression in foreground is vent from which the lava of the very recent Bonito flow escaped.



C. VERY RECENT CONELET NEAR SUNSET PEAK.

Photograph by A. E. Hackett, Flagstaff, Ariz.

An unnamed cone (Pl. XI, *B*) situated in the southeast part of the field illustrates the high degree of symmetry and perfect state of preservation exhibited by many of the basaltic cones. It is about 1,000 feet high, and the smoothness of the slopes is due to a loose covering of cinders. From its state of preservation, this cone would seem to be comparable with Cinder Cone of the Lassen Peak region, California—that is, it might well be not more than a few hundred years old. Its situation suggests, however, that it belongs to the earlier stage of the third period of eruption. The very small cone at its southern base is younger, but not of the very recent stage, according to the appearance of the lava flow associated with it.

Of the more dissected cones Red Mountain,[1] a few miles northwest of Slate Mountain, has been mentioned by Davis[2] as a promising specimen for study, and its structure has been described in some detail by Atwood.[3] The northeast slope has been strongly dissected by erosion and the internal structure well displayed (Pl. XII, *A*). The cone is composed entirely of fragmental material, for the most part compacted tuff, except a small lava flow on the southwest slope. The beds of tuff are thicker at the bottom of the cone and in general become thinner toward the summit as the area of the slopes increases. Broadly, this means that the volume of material ejected in the different outbreaks remained constant, but how constant could only be told by calculations of a quantitative nature. This feature, taken in connection with the even texture of the tuff as a whole, seems to indicate that the outbreaks were uniform in character throughout the life of the cone.

Scattered throughout the tuff are small bombs and fragments of lava that in places form solid layers. The pitted appearance of the beds at many points is due to the removal of the larger fragments of lava and bombs. The tuff also contains large quantities of beautifully clear plagioclase feldspar and black hornblende.

The beds of tuff have been eroded into a mass of short, stout pyramids, a typical badland topography. On account of the incoherence of the material composing the beds, these pyramids are not lasting, although temporary halts in their demolition are caused by thin and more firmly cemented beds of tuff and by the fragments of lava capping individual members.

Erosion has eaten a sufficient distance into the base of the cone on the northeast side to expose the very outer edges of the tuff beds formed in the earliest stages of eruption. These lowest beds have an outward dip of not more than 5°. The outward dip of the beds, however, gradually increases as the eroded slope is ascended, because the exposures are relatively nearer the center of the cone, until it reaches a maximum of 20° in the uppermost beds.

According to Atwood,[4] "rain and running water have removed all traces of the former crater." It was the writer's observation that the cone did not originally have a typical crater, and it may be suggested that if the valley on the southwest side (shown in fig. 1 of Atwood's article) is due to erosion, it may well represent erosion in an earlier cycle than that of the freshly dissected northeast slope, as the form may be considered mature. On the other hand, it is not impossible that the valley represents either a breach produced by an explosion or an original irregularity in the shape of the cone.

Sunset Peak, 10 miles east of the summit of San Francisco Mountain, is between 800 and 1,000 feet high and at its summit has a practically unbreached crater, about a quarter of a mile in diameter and 400 feet deep (Pl. XII, *B*). The slopes are thickly covered with black cinders and lapilli, representing the last eruptions of the cone or neighboring cones, but lava is exposed around the rim of the crater. The lava has been decomposed and bleached to yellowish and pinkish tones by fumarole action, and a few crystals of sulphur are found. Below the rim, especially on the southern outer slope of the cone, the color of the cinders grades successively through yellows, oranges, and reds into the original black of the lower slopes, and this feature has given the mountain its name. The cone has not been shattered by explosions nor has erosion produced any noticeable change of form, so that from its state of preservation it may be classed with the unnamed cone in the southeastern part of the field shown in Plate XI, *B*.

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[1] This cone probably belongs to the first general period of eruption, but may be described, for convenience, at this point.

[2] Davis, W. M., An excursion to the Grand Canyon of the Colorado: Bull. Mus. Comp. Zool. Harvard Coll., vol. 38, May, 1901, p. 193.

[3] Atwood, W. W., Red Mountain, Arizona—a dissected volcanic cone: Jour. Geology, vol. 14, No. 2, 1906, p. 138.

[4] Op. cit., p. 144.

The Bonito flow, which lies west of Sunset Peak, is the most accessible of the very recent cones and flows and some of its features may be briefly noted. No cone is associated with this flow. The lava escaped from a small vent opened through an older basalt flow of the third period and spread out quietly, filling an elongated depression between the older flows and cones. This vent may be seen in the foreground of the picture of Sunset Peak (Pl. XII, *B*). The extreme freshness of the lava, as well as the barrenness of the surface of the flow, is strikingly evident. Vegetation has not yet gained a foothold on it, except in a few places where fine cinders blown on the lava by the wind have furnished soil for the growth of some small shrubs. The contrast between the Bonito flow and one belonging to the earlier stage of eruption is well illustrated in Plate XII, *B*. Sufficient soil has accumulated on the older flow to support a scanty growth of pines, which are also found on the slopes of Sunset Peak.

To bring out fully the extreme freshness of these recent lavas, a small cone, about 50 feet high, belonging to the Bonito group is shown in Plate XII, *C*. No description is necessary to emphasize the perfection of detail here shown. It is such as might well be expected in a lava that had been erupted but a few years.

The most interesting point in relation to these latest cones and flows seems to be the determination of their age, but unfortunately the data available for such a purpose are very scanty. The most definite statement that can be made is that they are older than the pine trees growing at the edge of the Bonito flow west of Sunset Peak. This would make them not less than 300 years old. Not improbably they may be as much as 1,000 years old. The climate of the region, which has maintained the same general character all through later Quaternary time, and the nature of the lava both reduce weathering to a minimum.

CHAPTER IV.

GEOLOGIC HISTORY OF THE VOLCANIC FIELD AND ADJACENT COUNTRY.

CORRELATION OF EVENTS.

The sequence of volcanic events in the San Franciscan region is fixed almost wholly by the field relations of the lavas and may be correlated with some certainty with the general sequence of events in the surrounding Plateau country. This is especially true of the earliest and the latest volcanic phenomena. The difficulty arises when it is attempted to place these events in geologic time The southwestern part of the Colorado Plateau has been undergoing erosion for a period that considerably antedates the beginning of volcanic activity in the San Franciscan field. Contemporaneous sedimentary deposits are absent, except unfossiliferous alluvium. The only way the age of the physiographic cycles of the Plateau country, and consequently the time of the eruptive cycles of the San Franciscan field, can be determined is by correlation with the Basin Range country of southern Nevada.[1] That the correlation rests on a physiographic rather than a stratigraphic basis can not be urged against its acceptability, for the geologic changes that have occurred in the Plateau region are not local in character; they are the individual expression of forces that affected a very much wider area. This was stated by Gilbert [2] nearly 40 years ago as follows:

> The consideration of the phenomena presented in these and other localities [on the border between the Plateau and the Basin Ranges] leads to the conclusion that the Plateau is not a unit in history and origin, and that the only criterion by which it can be distinguished from the Range country is the original superficial one of table and ridge. The Plateau area has in part been longer and later submerged than adjacent regions and in part exempted from the action of forces that threw up mountain ridges along its borders. It has not, however, been entirely exempt and, differing from the Basin Range region only in the *degree* of disturbance, has not an absolute boundary.

Before volcanic activity began the San Franciscan field, in common with the region embraced in the present Plateau country, had been undergoing erosion for a long period, which began possibly in Eocene time. At the termination of the Miocene epoch widespread and pronounced faulting—the first period of faulting—marked out the Plateau region in approximately its present form and gave rise to the Basin Ranges of southern Nevada (and Arizona) as tilted block mountains. Erosion continued and reduced the Basin Ranges to mature forms. Contemporaneously local peneplains were developed, under favorable conditions, about the foot slopes of the ranges, and in the present Plateau country a highly developed peneplain covered thousands of square miles. As a result of this erosion the relief produced by the previous faulting was largely, and in places entirely, obliterated. This period is called the peneplain cycle of erosion, and it practically marked the end of the "great denudation" of the Grand Canyon district. At this time, then, the Plateau as now known did not exist. Instead the region was part of a gentle plain fronting mountain ranges situated in general to the west and south. This is all that may be said with any degree of assurance, and as may be seen the region presented a very different aspect from its present one.

FIRST GENERAL PERIOD OF VOLCANIC ACTIVITY.

The first general period of volcanic activity in the San Franciscan field was characterized by widespread eruptions of normal basalt in thin flows, mostly from local vents, accompanied by the building of small cones, but in part from fissures. It began shortly after the region had

[1] Robinson, H. H., A new erosion cycle in the Grand Canyon district, Ariz.: Jour. Geology, vol. 18, 1910, pp. 742-763. The results given in that paper will be used here without further reference.

[2] Gilbert, G. K., U. S. Geog. Surveys W. 100th Mer., vol. 3, 1875, p. 58.

been reduced to a peneplain, and before the peneplain had experienced any notable degree of dissection.[1] The eruptions are thus considered as having occurred in late Pliocene time. As this peneplain was of very wide extent and was developed equally over areas of hard and soft strata, it is presumable that the region at this time stood close to sea level. The climate may have been more moist than during the succeeding periods, as the basalt at some localities has weathered to a residual clay. Weathering so complete is associated, so far as known, only with the basalt of the first period of eruption and apparently can not be due to local causes.

UPLIFT AND EROSION INTERVAL FOLLOWING FIRST PERIOD OF ERUPTION.

The revival of erosive forces, following the development of the peneplain and the basalt eruptions, is supposed to have been due to a slight elevation of the land accompanied by faulting—the second period of faulting. This conclusion is based on general considerations rather than on specific observations, although Johnson[2] has described faulting on the Hurricane displacement near Toquerville, Utah, that may be referred to this period.

As the result of renewed erosion the soft strata of the Moencopie and other formations of the Shinarump group were stripped from the resistant Kaibab limestone over wide areas in the eastern part of the field, and the basalt of the first period of eruption, where it rested on them, was much reduced in area by undermining. On account of its greater hardness, however, the lava acted as a partial check to the removal of the soft underlying sediments and is now found capping many mesas and buttes. The amount of material eroded at different localities varied greatly. Thus near the contact between the Shinarump group and the Kaibab limestone in the vicinity of Flagstaff it was small. Along the east side of Anderson Mesa it was much greater, as the thickness of the strata in the mesa ranges from 400 to 500 feet. The maximum erosion was in the vicinity of Cedar Ranch, where 700 feet of strata were removed. At these localities the stripping extended to the Kaibab limestone. In the Little Colorado Valley, however, it did not do so, and the amount of erosion is uncertain, because the horizon to which the stripping did extend has not been determined. It appears to have been of the same magnitude as at the places above mentioned, to judge from the exposures at Black Point and along the eastern boundary of the volcanic field. It is evident, therefore, that a very considerable volume of strata belonging to the Shinarump group was eroded during this cycle in the eastern part of the region. In the western part of the field, where the basalt rested directly on the Kaibab limestone, conditions were in striking contrast to those in the eastern part. Both the basalt and the limestone offered so strong a resistance to erosion that stripping was impossible, and their removal was confined to the vicinity of drainage lines. In this section of the field an insignificant volume of material was removed.

The difference between the extent of erosion in the eastern and western parts of the region was due entirely to differences in the character of the rocks and not to more active erosion in one locality than the other. This is shown by the relative conditions on the two sides of the contact between the Shinarump group and the Kaibab limestone near Flagstaff and Anderson Mesa. The difference suggests how erroneous might be an idea of the erosion during this period if observations were restricted to only one part of the region.

Erosion continued until a mature topography of low relief was developed on the resistant Kaibab limestone in the areas from which the Shinarump group had been removed and at some horizon in the Shinarump group itself in the Little Colorado Valley. It is probable that local peneplains were developed in the Shinarump group in areas where the highly resistant Kaibab limestone could limit base-leveling. In view of the development of a mature topography of slight relief on so resistant a formation as the Kaibab limestone, the conclusion seems justified that the region at this time, as during the peneplain cycle, stood at no great height above the sea.

[1] Robinson, H. H., The Tertiary peneplain of the Plateau district and adjacent country in Arizona and New Mexico: Am. Jour. Sci., 4th ser., vol. 44, 1907, pp. 109–129.

[2] Johnson, D. W., A geological excursion in the Grand Canyon district: Proc. Boston Soc. Nat. Hist., vol. 34, No. 6, 1909, pp. 154–161.

SECOND GENERAL PERIOD OF VOLCANIC ACTIVITY.

The second general period of activity in the region was marked by the eruption of lavas ranging from andesites to rhyolites. Six large cones and perhaps a dozen small ones were formed, and in addition there were contemporaneous laccolithic intrusions. These events probably occurred during or soon after the development of the mature topography of the postpeneplain cycle of erosion, which places them in the first part of the Quaternary period.

The direct evidence in favor of placing these eruptions in the postpeneplain cycle is very meager but seems fairly conclusive. Most significant would seem to be a deposit of dacite pumice, which rests in a shallow depression in the Kaibab limestone 1¼ miles east of Flagstaff and south of the railroad. Since the pumice was laid down the erosion of the general surface in this vicinity has been very slight. The purity of the material and the diversity in the size of the blocks would seem sufficient proof that the pumice was deposited in its present position at the time of its eruption. The homogeneity of the deposit is in strong contrast to the heterogeneity of the material generally found in the inclosed basins of the region. The position of the west foot slope of Elden Mountain with respect to Switzer Mesa also points to the conclusion that the lava of this mountain was erupted when the country had essentially the same general configuration as at present. (See fig. 19, p. 78, and cross sections, fig. 23, p. 83.) The evidence at these two localities, however, only fixes the maximum age of the eruptions of the second period as not older than the mature topography of the postpeneplain cycle of erosion. It does not fix their minimum age because the mature topography, owing to the existing climatic conditions, has preserved its original features down to the present time. The minimum age of the eruptions has to be determined by relative evidence based principally on the erosion of the large cones and the small basalt cones of the following period of eruption. In general the greater age of the eruptions of the second period is shown by the fact that the large volcanoes have lost, on the average, 8 per cent of their original volume since they became extinct, whereas the basalt cones of the third period as a whole are remarkably well preserved, as may be seen from the illustrations given in the preceding chapter. The comparatively slight erosion of the large cones alone would seem to indicate a short duration of time since they became extinct, but this is only suggestive, because nothing is definitely known as to the rate of erosion. Although there is no direct evidence to support the inference, it is believed that the eruptions of the second period occurred before the extensive faulting which introduced the present youthful canyon cycle of erosion.

UPLIFT AND EROSION FOLLOWING SECOND PERIOD OF ERUPTION.

A period of broad crustal uplift accompanied by warping and faulting—the third period of faulting—followed the postpeneplain cycle of erosion and the eruptions of the second period of volcanic activity. The region was raised, at a maximum, over 6,000 feet above its position at the close of the postpeneplain cycle, if it is granted that the mature topography of that cycle could not have been developed at a significant height above sea level. The major faulting of the plateau in general followed the same lines as the earlier displacements, but in addition there was considerable minor faulting along new lines throughout the region. This period of uplift introduced the present or canyon cycle of erosion, during which the canyons of the region have been cut and cliff profiles refreshed. There has also been some further stripping of the soft strata of the Shinarump group where they are favorably situated to erosion. This has occurred almost entirely in the little Colorado Valley, where on account of the small rainfall—about 5 inches a year at present—wind has been a more important factor than water. In those localities where the Kaibab limestone forms the surface rock erosion has been so slight that it can not be certainly detected except as canyon cutting.

THIRD GENERAL PERIOD OF VOLCANIC ACTIVITY.

The third and last general period of activity, like the first, was characterized by the eruption of basalt from scattered vents about which lava and cinder cones were built. Two stages of activity are recognized. The earlier stage was by far the more important, for during it over

95 per cent of the cones were formed and lava erupted. The later stage was marked by the formation of perhaps a dozen cones, conelets, and lava flows, which are to-day perfectly preserved. The cones and lavas cover about 1,200 square miles. They are thus less widely spread than the cones and lavas of the first period, which extend unbrokenly far beyond the limits assigned to the San Franciscan field. They are more widely scattered than the cones and lavas of the second period. The area covered by them, however, is rather symmetrically located about the cones of the second period (see Pl. III, p. 20), and this would seem to indicate close magmatic relationship.

The eruptions of this period apparently began not long after the close of the second period of activity and probably continued with some interruption down to the present time. An early age would seem to be indicated for two cones in Black Bill Park, east of San Francisco Mountain, which are nearly buried beneath alluvial fans associated with that volcano. However, if these cones are of average size they do not antedate the entire mass of alluvium but rest on it at an intermediate horizon. Some of the flows of this period followed the mature valleys of the postpeneplain cycle of erosion, as, for example, on the edge of the field southeast of Flagstaff and north of Williams. At both of these localities small canyons were later cut along the contact of the flow with the side of the mature valley. This may be interpreted as indicating an early date for these flows. The situation of numerous basalt vents well up on the main slopes of Kendrick Peak may mean a close time relation between the eruptions of the second and third periods. However, as a similar clustering of vents does not occur at the other large cones, the phenomenon at Kendrick Peak may simply mean that the basalt found an easy channel of escape in the older conduit, through which the lavas of the second period rose.

The recency of many of the eruptions of the earlier stage of the third period is shown by the notably well-preserved condition of the cones. This is, however, not wholly conclusive, for the hardness of the lava or the perviousness of the cinders composing them delays erosion, especially in this arid to semiarid region. The evidence furnished by the relation of the lavas to the old basalt-capped mesas and to encanyoned watercourses is more definite. In the Little Colorado Valley and at Cedar Ranch the basalt overran the edges of mesas 200 to 700 feet in height, and so far as can be judged there has been no appreciable retreat of the mesa cliffs since that event. At these localities, however, conditions are favorable to rapid erosion, as the strata underlying the old basalt cap are soft shales and marls. At Grand Falls, on Little Colorado River, a lava flow completely filled a steep-sided canyon, 125 feet deep, causing a diversion of the river to a new course. The recency of this event is clearly attested by the slight headway the river has made in establishing its new course, although the stream is a major tributary of the Colorado.

The general conclusion is reached that the eruptions of the earlier stage of the third period of activity covered a considerable interval, beginning not long after the close of the second period and extending into comparatively recent geologic time. That is, they certainly occurred during the Quaternary period and presumably during the later part of that period.

But of even more recent date are the small number of cones and flows of the later stage of the third period which are situated in the eastern part of the field. The state of preservation of these cones and flows is so perfect that they may well date from historic time. However, as they occur in an arid to semiarid region, where weathering is reduced to a minimum, they would naturally retain a fresher appearance than in a humid climate. They are probably not less than 300 years old, as judged from the pine trees that grow along the border of the Bonito flow, and they may be (in round numbers) 1,000 years old.

In view of the recency of these eruptions it is an interesting question whether volcanic activity has actually ceased in this region. Broadly speaking, it may be said to have ceased. There may be further small outbreaks of basalt, but this does not seem probable in view of the insignificant volume of the latest eruptions compared with the total volume of the lava of the last general period of activity. These very latest outbreaks may be looked upon as representing the final feeble manifestations of a long and very complete cycle of volcanism.

The general geologic history of the region embracing the San Franciscan volcanic field may be summarized, in conclusion, as follows:

1. Period of folding and flexing during the later half or at the close of the Eocene epoch.
2. Erosion period during the Miocene epoch.
3. First period of faulting at close of the Miocene epoch. A period of extensive faulting. It is correlated with the faulting that gave rise to the Basin Ranges of southern Nevada as tilted block mountains.
4. The peneplain cycle of erosion during the Pliocene epoch. The erosion of the Miocene and Pliocene epochs, which is considered as constituting the later and greater part of the period of the great denudation, closed with the widespread development of a peneplain. This is correlated with the mature topography and local peneplains of the Basin Range country of southern Nevada and of Arizona. Relief produced by previous faulting was largely and at some localities entirely obliterated. The first general period of volcanic activity in the San Franciscan region, marked by widespread eruptions of basalt, occurred shortly after the development of the peneplain and most probably while the region still stood close to sea level.
5. The second period of faulting at the close of the Pliocene epoch. Movements were probably of less magnitude than those of the first and third periods.
6. The postpeneplain cycle of erosion during the first part of the Quaternary period. Widespread stripping of Permian and Triassic strata occurred, and a mature topography of low relief was developed, principally on the Kaibab limestone, at a horizon ranging from the level of the peneplain to 1,000 feet below it. Further retreat of the high cliffs on the north and east sides of the district took place. Land stood at no great height above the sea. The second general period of volcanic activity is placed in this cycle.
7. The third period of faulting, with broad regional uplift, during the middle or latter part of the Quaternary period. Region was raised 4,000 to 6,000 feet above the position it occupied at the close of the postpeneplain cycle of erosion.
8. The canyon cycle of erosion, during the later part of the Quaternary period. Marked by the development of a canyon system of drainage of extreme youthfulness and the refreshing of cliff profiles. Erosion otherwise was very slight. Colder atmospheric conditions prevailed during part of this cycle, at least, as indicated by the existence of a small glacier on San Francisco Mountain, and during this time the large cones were heavily mantled with alluvium. The third general period of eruption in the San Franciscan field occurred during this last cycle.

CHAPTER V.

PETROGRAPHY.

METHOD OF TREATMENT.

The detailed description and classification of the igneous rocks of the San Franciscan volcanic field are presented in this chapter. The broader subjects of the serial relations of the rocks, the differentiation and composition of the magma, etc., are considered in the following chapter. Each rock is described under the headings "Occurrence," "Megascopic characters," "Microscopic characters," "Crystallinity," "Chemical composition," and "Mineral composition." A few of the descriptions contain an additional section dealing with some special feature. The first three headings require no comment, but certain points in regard to the others may be mentioned.

Under "Crystallinity" is given the micrometric analysis, made by the Rosiwal method, of the type and additional specimens. As most of the rocks are lavas containing much glass or submicroscopic material, this analysis shows, in a way, the extent to which the rock has crystallized and the minerals that have separated out. It should be noted that under "groundmass" are included all minerals of an average diameter less than 0.01 millimeter, the smallest division of the micrometer. In general this arbitrary limit has caused little confusion between groundmass and phenocrysts, as may be seen from the results given in this chapter and the following one. Statements in regard to the crystallinity of the groundmass are given under "Microscopic characters." The analysis gives the complete crystallinity only for a small number of holocrystalline rocks. It does not give the actual mineral composition of these rocks, however desirable this may be for a physicochemical discussion, because of the impossibility of distinguishing in every instance between different minerals of similar appearance.

The method adopted for micrometric analysis, after some experimenting, was to make two sets of traverses at right angles, one of which was generally parallel to the flow structure of the lava. On account of the porphyritic nature of the rocks it was necessary, in order to attain reliable results, to measure longer distances than 100 times the average grain, the distance suggested by Rosiwal for holocrystalline granular rocks. The average distance traversed in the rocks of the San Franciscan field for a single analysis was 10 centimeters. Duplicate analyses were generally made in order to test the method on glassy to fine-grained porphyritic lavas and fine-grained holocrystalline rocks. For a number of rocks it has been possible to check the results of the micrometric analysis with the calculated mineral composition. As will be seen in the following pages, the agreements are very satisfactory and show that the Rosiwal method can be applied with considerable confidence to rocks whose average grain is little greater than the thickness of the thin section.

Each chemical analysis represents the composition of a single rock fragment selected after an inspection of numerous thin sections as the one most typical of the whole rock mass. For the uses made of the analyses, which are described in the next chapter, it might have been better to make an analysis of a composite of specimens taken from different parts of each rock mass. The method adopted, however, was considered satisfactory because the thin sections showed that the several rock masses were fairly uniform in character. Most of the specimens chosen for analysis were entirely fresh. In a few specimens a slight alteration of the dark minerals resulted in incorrect analytical values for ferric and ferrous iron compared with those of the fresh rock. It has been possible, however, to obtain approximately correct values for these oxides from the micrometric analyses in connection with the calculated mineral composition. They are placed in brackets after the chemically determined amounts and have been used for calculating the average composition of the lavas.

The complete mineral composition of each rock as calculated from the chemical composition is given under the heading "Mineral composition." It would be most desirable to have it represent the actual mineral composition, but this is not possible under the existing conditions. It is thus necessary to give the bulk amounts of orthoclase and albite, disregarding the fact that soda orthoclase, anorthoclase, or microperthite may actually be present. It is necessary to assume that all the plagioclase is the same as the few crystals whose composition was actually determinable. As a matter of convenience, ilmenite is in all cases included with magnetite. On the whole the actual composition of the dark minerals may be more satisfactorily determined than that of the feldspars. An idea of the general method of calculating the mineral composition, and the assumptions it involves, may be obtained from detailed examples in the following pages. It may be said here that these statements of complete mineral composition, as well as the micrometric analyses, have made it possible to express several serial relationships that exist between the individual lavas which would otherwise have escaped detection. It is strongly urged that quantitative statements of the actual mineral composition, as nearly as it can be determined, and of the crystallinity, when possible, should be considered as essential parts of every detailed petrographic description.

The approximate order in which the rocks are described and their position in the "quantitative system of classification" are given in the following table:

Igneous rocks of the San Franciscan volcanic field.

[Numerals in parentheses indicate the number of rocks described under that name.]

Name.	Position in quantitative system.	Symbol.
Biotite rhyolite (1)	Liparose (1)	I.4.1.3.
Biotite-soda granite porphyry (1)		
Biotite-soda rhyolite (1)	Kallerudose (4)	I.4.1.4.
Riebeckite-soda rhyolite (1)		
Riebeckite-soda granite porphyry (1)		
Biotite dacite (2)		
Biotite-hornblende dacite (1)		
Hypersthene-soda dacite (1)	Lassenose (7)	I.4.2.4.
Hypersthene-hornblende-soda dacite (1)		
Hornblende-soda dacite (2)		
Pyroxene dacite (1)	Tonalose (2)	II.4.3.4.
Hypersthene dacite (1)		
Hornblende dacite (1)	Dacose (1)	II.4.2.4.
Pyroxene latite (1)	Tonalose-andose (1)	II.4,5.3.4.
Pyroxene-hornblende latite (1)	Tonalose-andose-dacose-akerose (1)	II.4,5.2,3.4.
Augite andesite (2)		
Augite andesite-basalt (1)	Andose (4)	II.5.3.4.
Hornblende-soda andesite-basalt (1)		
Augite basalt (2)	Auvergnose (2)	III.5.4.3.

REFERENCE TYPES.

CLASSIFICATION.

The rocks of the San Franciscan region have been classified by comparison with certain "type" rocks representing the groups to which they belong or are related. The comparison is based on chemical analyses and quantitative statements of the mineral composition. The method is one of convenience and has been adopted because of the greater satisfaction derived from the use of definite types than of the present indefinite groups.

It is believed that the need of definite types for general purposes of comparison will be recognized. Without such types, statements that a certain oxide is high or low or that a certain mineral is present in large or small amount have but a vague significance. The main types that have been calculated are the granite-rhyolite, syenite-trachyte, diorite-andesite, and gabbro-basalt, and from these intermediate members have been derived. The chemical types are based on the analyses of certain subrangs of the quantitative system of classification as given in the Washington and Washington-Roth tables of analyses.[1] They represent, so far

[1] Washington, H. S., Chemical analyses of igneous rocks: Prof. Papers U. S. Geol. Survey Nos. 14 and 28, 1903 and 1904.

as their method of calculation permits, the prevailing opinion in regard to the composition of the four groups above mentioned. The type mineral composition has been calculated from the chemical composition. The two are, therefore, interdependent and, with certain qualifications, may be used with equal facility in the classification of the rocks. The decidedly uncrystallized condition of most of the rocks of the San Franciscan region, or at least the submicroscopic size of most of the minerals, tends to lay emphasis on chemical composition as a basis for classification. On general principles, however, the actual quantitative mineral composition is preferable to the chemical composition.

The trend of physicochemical investigations of rock minerals and magmas seems to indicate that in the not distant future the classification of igneous rocks will rest on an adequate understanding of their origin and relationships—that is, it will rest on a natural basis. It would appear that the important factor for classifying rocks in the future, as in the past, will be the actual mineral composition, with the difference that the complete instead of the partial composition will be used. If this idea is correct, it is important to acquire the habit of thinking of rock composition quantitatively, for a quantitative system of classification can hardly come into general use until such a habit has been acquired. It will be found that a quantitative conception of igneous-rock composition, entirely aside from classification, will make clear many relationships which would otherwise be obscure or remain hidden.

The facility with which rocks may be studied by means of the microscope has tended, it is believed, to overemphasize their diversity of composition. This observed diversity is a source of confusion because its significance can not be fully appreciated. A broad consideration of igneous rocks shows that their diversity, with respect to chemical composition at least, is not great. The vast majority fall within rather narrow limits. This is graphically illustrated by Plate VIII in Iddings's paper "Chemical composition of igneous rocks."[1] (See also fig. 34, p. 202.) It is also revealed by the grouping of analyses by the quantitative system of classification in the Washington and Washington-Roth tables. For example, 94 per cent of the analyses fall into but 48 per cent of the orders (the second largest division), 88 per cent are in 41 per cent of the rangs, and 78 per cent are confined to 25 per cent of the subrangs for which analyses are known. Actually 78 per cent of the analyses fall into only 6 per cent of the subrangs that are provided, a fact which indicates the "ready-made" nature of the system, if such an expression may be used without prejudice to several most excellent features. The actual number of orders containing the 94 per cent of analyses is 13, of rangs 35, and of subrangs 52. Without regard to the details of equivalence of the quantitative system to prevailing systems, it is evident that a large majority of igneous rocks may be grouped under a small number of chemical types.

The types used in this report are given in the following sections. They represent, to some extent, a redefinition of existing rock names, which should be borne in mind in reading this chapter and the following one. There are so many difficulties in the way of converting qualitative into quantitative definitions that these types are offered simply as a means toward an end, not with the idea that they should be final. Statements as to the relative amounts of the oxides are based on comparison with the average igneous rock of the earth as calculated by Washington.[2] The mode is supposed to consist of the commonest minerals which compose the respective type. The granite-rhyolite type, for example, consists essentially of quartz and alkali feldspars, with a small amount of oligoclase and commonly biotite. Some types may have either biotite, hornblende, or pyroxene as the common dark mineral, and the mode will vary somewhat, depending on which one is present. The relative amounts of albite and plagioclase may be considerably changed by variations in the composition of the plagioclase. It is possible, also, for a rock of a given chemical composition to crystallize in two different sets of minerals. One of these, however, will generally be common and the other rare. In general, the type modes can not be exactly calculated, so that the manner in which they are here used is somewhat experimental. In the granite-rhyolite and syenite-trachyte types lime has been put into orthoclase and albite in order to reduce the amount of plagioclase. Magnesia generally fixes the amount of biotite, hornblende, or augite, the general composition of which

[1] Prof. Paper U. S. Geol. Survey No. 18, 1903.

[2] Prof. Paper U. S. Geol. Survey No. 14, 1903, p. 108.

is adjusted so as to do away, if possible, with a final excess of alumina and leave ferric iron and titania equal to ferrous iron. In some cases it has been necessary to assume the presence of hypersthene in order to reduce the excess of alumina.

To designate the so-called dark minerals, namely, the various members of the pyroxene, amphibole, mica, and other groups, it is proposed to use the adjective *calfemic*. It indicates that these minerals contain some of the following oxides: Lime (*ca*), alumina, alkalies (*al*), iron (*fe*), and magnesia (*m*). The syllable *al* is inserted to cover the micas and alkali members of the pyroxene and amphibole groups. The adjective *salic* [1] is used in the sense in which it was originally proposed. Salic and calfemic are thus practically synonymous respectively with "light" and "dark," or leucocratic and melanocratic.

TYPES.

GRANITE-RHYOLITE.

The granite-rhyolite type is based on the analyses in I.3.1.2, 3, and 4 and I.4.1.2, 3, and 4.[2] The number of analyses is 217, of which over 90 per cent are classified in this group according to the prevailing system. The chemical and mineral composition are as follows:

Chemical and mineral composition of granite-rhyolite type.

SiO_2	73.5	Quartz	31.4
Al_2O_3	13.5	Orthoclase	28.2
Fe_2O_3	1.4	Albite	28.2
FeO	1.0	Oligoclase (Ab_4An_1)	5.0
MgO	.3	Biotite	5.6
CaO	.6	Magnetite	1.2
Na_2O	3.7	Apatite	.2
K_2O	5.1	Water	.6
H_2O	.7		100.1
TiO_2	.3		
P_2O_5	.1		
MnO	.1		
	100.3		

This type is chemically marked by high silica, rather high potash, medium soda, slightly low alumina, and low iron, magnesia, and lime. The molecular ratio of potash to soda is practically 1 : 1. Mineralogically the type consists predominantly of quartz, orthoclase, and albite, which compose 87.8 per cent of the rock, with subordinate oligoclase and calfemic minerals.

SYENITE-TRACHYTE.

The syenite-trachyte type is based on the analyses in I.5.1.3 and I.5.2.3. The number of analyses is 44, most of which are classified in this family according to the prevailing system. The chemical and mineral composition are as follows:

Chemical and mineral composition of syenite-trachyte type.

SiO_2	61.7	Quartz	3.7
Al_2O_3	18.5	Orthoclase	38.8
Fe_2O_3	2.9	Albite	37.3
FeO	2.1	Oligoclase (Ab_3An_1)	10.0
MgO	.5	Hornblende	5.0
CaO	1.9	Magnetite	4.4
Na_2O	5.1	Apatite	.2
K_2O	6.3	Water	.8
H_2O	.8		100.2
TiO_2	.3		
P_2O_5	.1		
MnO	.1		
	100.3		

[1] Cross, W., Iddings, J. P., Pirsson, L. V., and Washington, H. S., Quantitative classification of igneous rocks, 1903, p. 116.

[2] Symbols refer to subrangs of the quantitative system of classification. See Prof. Papers U. S. Geol. Survey Nos. 14 and 28.

This type is clearly an alkali syenite. It has been taken because of its greater definiteness compared with the conception of syenite as an orthoclase and acidic plagioclase rock. It conforms to the rather common definition of syenite and trachyte as consisting essentially of alkali feldspars. The recognition of the alkali syenite and monzonite types has cut down the syenites proper to a small group. Chemically the type has medium silica and high alkalies. Alumina is rather high, whereas iron, magnesia, and lime are low. The molecular ratio of potash to soda is 1 : 1.25. Mineralogically orthoclase and albite in equal amounts form three-quarters of the type, and oligoclase (Ab_3An_1) and calfemic minerals, with a small amount of quartz, form one-quarter. The presence of quartz indicates that the type is slightly too acidic, as typical syenite should be quartz-free. It may be noted that in the analyses of syenites quoted by Rosenbusch[1] and Kemp[2] silica equals 58 per cent, whereas in the trachytes it is 63 per cent. This is because the holocrystalline syenites have been classified on the basis of complete mineral composition and the absence of quartz has been a critical factor. The hypocrystalline trachytes have been classified on incomplete mineral composition and uncrystallized quartz in the groundmass has not been considered. The same difference exists between diorites and andesites. It illustrates one of the unavoidable defects of using qualitative mineral composition as a basis of classification.

DIORITE-ANDESITE.

The diorite-andesite type is based on the analyses in II.4.3.3 and 4 and II.5.3.3, 4, and 5. The number of analyses is 373, of which about three-quarters represent rocks classified as diorites and andesites, or closely related members. The chemical and mineral composition are as follows:

Chemical and mineral composition of diorite-andesite type.

SiO_2	57.2	Quartz	9.6
Al_2O_3	16.7	Orthoclase	13.3
Fe_2O_3	3.7	Albite	8.5
FeO	4.1	Andesine (Ab_1An_1)	41.6
MgO	3.9	Augite	10.0
CaO	6.4	Hypersthene	9.0
Na_2O	3.5	Magnetite	6.3
K_2O	2.3	Apatite	.4
H_2O	1.3	Water	1.3
TiO_2	.7		100.0
P_2O_5	.2		
MnO	.2		
	100.2		

This type has medium silica, alumina, magnesia, and soda. Potash is slightly low, iron and lime slightly high. Mineralogically the type consists predominantly of plagioclase (Ab_1An_1) and calfemic minerals. Quartz, orthoclase, and albite form slightly less than one-third of the total. If the plagioclase were Ab_4An_3, there would be practically no albite. Hypersthene is necessary in order to prevent a final excess of alumina. Diorites in general contain less quartz than the type, whereas many andesites contain much more. The difference is due to the fact that diorites have been classified on complete mineral composition, andesites on incomplete composition. In the andesites, as a rule, only the calfemic minerals and plagioclase crystallize in determinable individuals, and from these the position of the rock is fixed. The groundmass, which forms the greater part of the rock, is ordinarily neglected. For this reason the type here given, as it includes many andesites, may be considered slightly too salic.

[1] Rosenbusch, H., Elemente der Gesteinslehre, 1898, pp. 106, 268–269.
[2] Kemp, J. F., Handbook of rocks, 1904, pp. 38, 42.

GABBRO-BASALT.

The gabbro-basalt type is based on the analyses in II.5.4.3, III.4.3.4, III.5.3.4 and 5, III.5.4.3, and III.5.5. The number of analyses is 246, of which about three-quarters represent rocks classified as gabbros and basalts, or closely related members. The chemical and mineral composition are as follows:

Chemical and mineral composition of gabbro-basalt type.

SiO_2	48.0	Orthoclase	3.8
Al_2O_3	16.3	Labradorite (Ab_6An_7)	52.0
Fe_2O_3	4.0	Augite	26.2
FeO	7.6	Olivine	9.0
MgO	7.3	Magnetite	7.2
CaO	9.9	Apatite	.7
Na_2O	2.8	Water	1.4
K_2O	1.1		100.3
H_2O	1.4		
TiO_2	1.4		
P_2O_5	.3		
MnO	.2		
	100.3		

Chemically the type has rather low silica and alkalies, medium alumina and ferric iron, and high ferrous iron, magnesia and lime. Mineralogically it consists almost wholly of labradorite (Ab_6An_7) and calfemic minerals. The chief calfemic mineral is hypersthenic augite; olivine is present in small amount. The plagioclase seems somewhat acidic, but is required by the method employed of calculating the mode. The method is the same as that used in obtaining the mode of the basalt of Kendrick Peak, which gave correct results.

GRANITE-RHYOLITE-SYENITE-TRACHYTE.

This type consists of equal parts of the granite-rhyolite and the syenite-trachyte types. The chemical and mineral composition are as follows:

Chemical and mineral composition of granite-rhyolite-syenite-trachyte type.

SiO_2	67.6	Quartz	18.4
Al_2O_3	16.0	Orthoclase	30.7
Fe_2O_3	2.2	Albite	32.5
FeO	1.6	Oligoclase (Ab_3An_1)	8.8
MgO	.4	Biotite	7.0
CaO	1.2	Magnetite	2.0
Na_2O	4.4	Apatite	.2
K_2O	5.7	Water	.5
H_2O	.7		100.1
TiO_2	.3		
P_2O_5	.1		
MnO	.1		
	100.3		

Chemically the type has rather high silica and alkalies, medium alumina, and low iron, magnesia, and lime. Mineralogically the type is decidedly salic, as quartz, orthoclase, and albite form over three-quarters of the total. Hornblende may be the chief calfemic mineral as well as biotite, in which case the amounts of the salic minerals would be slightly changed.

GRANITE-RHYOLITE-DIORITE-ANDESITE.

The granite-rhyolite-diorite-andesite type consists of equal parts of the granite-rhyolite and diorite-andesite types and is therefore midway between them. The chemical and mineral composition are as follows:

Chemical and mineral composition of granite-rhyolite-diorite-andesite type.

SiO_2	65.3	Quartz	19.5
Al_2O_3	15.1	Orthoclase	22.0
Fe_2O_3	2.6	Albite	19.6
FeO	2.6	Andesine (Ab_1An_1)	21.2
MgO	2.1	Hornblende	10.0
CaO	3.5	Hypersthene	3.6
Na_2O	3.6	Magnetite	3.3
K_2O	3.7	Apatite	.4
H_2O	1.0	Water	.8
TiO_2	.5		100.4
P_2O_5	.2		
MnO	.1		
	100.3		

Chemically this type has rather high silica, medium alumina and alkalies, and slightly low iron, magnesia, and lime. Mineralogically it consists of approximately equal parts of quartz, orthoclase, albite, andesine, and calfemic minerals. The salic minerals form 82.3 per cent of the total. This type would appear to be more or less equivalent to quartz monzonite, dellenite, and adamellite, or to quartz diorite and dacite. In general the qualitative definitions are sufficiently elastic to embrace a considerable range of equivalencies. The type contains, however, somewhat more orthoclase, albite, and calfemic minerals, less plagioclase and quartz than those rocks as qualitatively defined. It classifies in the quantitative system as adamellose but near toscanose. The average dacite, based on all the analyses of rocks specifically so named in the Washington tables, classifies as yellowstonose. If the plagioclase in this average dacite is Ab_1An_1, it equals 28 per cent and albite is 21 per cent when hornblende is the calfemic mineral. To reduce albite to strictly subordinate amount the plagioclase would have to be at least Ab_2An_1, which seems too acidic a composition for the average. If igneous rocks grade into one another, the type here given, midway between the granite-rhyolite and diorite-andesite types, would seem preferable to one unsymmetrically placed. It will be spoken of hereafter as the dacite type.

SYENITE-TRACHYTE-DIORITE-ANDESITE.

The syenite-trachyte-diorite-andesite type is composed of equal parts of the syenite-trachyte and diorite-andesite types. It may be considered the equivalent of monzonite and latite and will be spoken of as such. The chemical and mineral composition are as follows:

Chemical and mineral composition of syenite-trachyte-diorite-andesite type.

SiO_2	59.4	Quartz	6.4
Al_2O_3	17.6	Orthoclase	25.1
Fe_2O_3	3.3	Albite	25.7
FeO	3.1	Andesine (Ab_4An_5)	23.0
MgO	2.2	Hornblende	12.0
CaO	4.2	Hypersthene	2.1
Na_2O	4.3	Magnetite	4.4
K_2O	4.3	Apatite	.4
H_2O	1.0	Water	.8
TiO_2	.5		99.9
P_2O_5	.2		
MnO	.1		
	100.2		

This monzonite-latite type has medium silica and ferric iron, slightly high alumina and alkalies, and slightly low ferrous iron, magnesia, and lime. Mineralogically about equal amounts of orthoclase, albite, and labradorite (Ab_4An_5) form three-quarters of the type; calfemic minerals and a small quantity of quartz form one-quarter. It differs notably from the granite-rhyolite-diorite-andesite (dacite) type in having lower quartz and somewhat higher alkali feldspars.

DIORITE-ANDESITE-GABBRO-BASALT.

The diorite-andesite-gabbro-basalt type is formed by equal parts of the diorite-andesite and gabbro-basalt types. The chemical and mineral composition are as follows:

Chemical and mineral composition of diorite-andesite-gabbro-basalt type.

			Normal mode.	Abnormal mode.
SiO_2	52.6	Quartz	4.4	11.9
Al_2O_3	16.5	Orthoclase	10.0	8.3
Fe_2O_3	3.9	Albite	9.3	3.0
FeO	5.9	Labradorite (Ab_3An_4)	41.8	34.5
MgO	5.6	Augite	16.0	....
CaO	8.2	Hypersthene	5.7	....
Na_2O	3.2	Olivine	5.0	....
K_2O	1.7	Hornblende	....	35.0
H_2O	1.2	Magnetite	6.4	6.2
TiO_2	1.1	Apatite	.7	.7
P_2O_5	.3	Water	1.0	.9
MnO	.2			
			100.3	100.5
	100.4			

Chemically the type has rather low silica and alkalies, nearly medium alumina and ferric iron, and rather high ferrous iron, magnesia, and lime. The normal mineral composition is principally labradorite (Ab_3An_4) and pyroxene. Quartz, alkali feldspars, olivine, and magnetite are present in subordinate amounts, but together they form over one-third of the type. An uncommon or abnormal mode is that which has hornblende for the calfemic mineral. The effect of the hornblende is to increase quartz and decrease albite as compared with the pyroxene mode. The hornblende mode of this type is suggested by the basic segregations in the dacitic lavas of the San Franciscan region.

THE RHYOLITIC LAVAS.

OCCURRENCE AND GENERAL CHARACTER.

Rhyolitic lavas occur at Sitgreaves Peak, San Francisco Mountain, Kendrick Peak, O'Leary Peak, and Sugarloaf Hill. They have typical rhyolitic textures and are chemically distinguished by the predominance of soda over potash. Intrusive representatives of the rhyolites, which occur at San Francisco Mountain and Marble Hill, have the same chemical and mineralogic composition as the lavas, but on account of their different texture are classified as granite porphyries. The porphyry of San Francisco Mountain is richer in soda and iron than the average and contains almost no lime and magnesia; it has an excess of alkalies over alumina, and the calfemic minerals are iron-soda amphiboles, for the most part riebeckite.

Soda-rich members of the granite-rhyolite group are commonly found in regions where members of the syenite-trachyte or related families are dominant. This is true in western Texas, Norway, Sardinia, and Abyssinia. Although such is not the association in the San Franciscan field it is interesting to note that of the two commonest rock types of the second period of eruption, to which the soda rhyolites belong, one is a latite and the other a soda dacite—that is, a lava with a trachytic cast.

No. 1. BIOTITE RHYOLITE (LIPAROSE, I.4.1.3).

Occurrence.—Biotite rhyolite is found only at Sugarloaf Hill and the associated rhyolite area on the east slope of San Francisco Mountain.

Megascopic characters.—The lava (1866)[1] of Sugarloaf Hill is light gray or lavender in color and has a noticeably banded structure produced by the alternation of thin compact and

[1] Numbers in parentheses in the descriptions are the specimen numbers in collection of rocks from the San Franciscan field.

porous layers. The texture is very uniform, well described as pasty, and the feel is finely rough. The groundmass is aphanitic and contains a small number of phenocrysts of quartz, feldspar, and light-brown biotite. North of Sugarloaf Hill the rhyolite occurs in two varieties. One (2227) is gray in color and has a uniform stony texture. The groundmass is aphanitic and contains only phenocrysts of biotite averaging not over 2 millimeters in diameter, which constitute about 2 per cent of the rock. The second variety (2229) is light brown in color and has a texture similar to the lava of Sugarloaf Hill. Phenocrysts of biotite occur in smaller numbers than in the first variety but are of larger size. A subvariety (2228) is formed by the alternation of the two main varieties in fine bands, which clearly bring out the flow structure.

Microscopic characters.—The groundness in general consists of about equal parts of microcrystalline feldspar and quartz and of glass. Only slight evidence of flow structure is seen in the lava of Sugarloaf Hill, because the crystals of feldspar and quartz are nearly equidimensional, but it is shown in the rhyolite of the northern part of the area by lath-shaped feldspars in parallel arrangement. Phenocrysts constitute about one-quarter of the rock and in order of abundance are alkali feldspar, plagioclase (Ab_4An_1), quartz, and biotite. The first three tend to form clusters, in which the order of crystallization is plagioclase, alkali feldspar, and quartz. Where their growth has not been hindered the alkali feldspars and plagioclase occur in tabular and prismatic crystals, which average about 0.6 by 1.8 millimeters and 0.3 by 0.7 millimeter, respectively, in cross section. The quartz is intermediate in size and commonly corroded. The biotite and the small amount of magnetite are both slightly altered. The biotite averages 0.06 by 0.5 millimeter in cross section and the magnetite 0.06 millimeter in diameter.

Crystallinity.—A general idea of the extent to which the lava has crystallized may be obtained from the following approximate micrometric analysis:

Approximate micrometric analysis of biotite rhyolite of Sugarloaf Hill.

Groundmass	87.0
Quartz	1.0
Alkali feldspars	8.0
Oligoclase (Ab_4 An_1)	3.0
Calfemic minerals	1.0
	100.0

As may be seen by comparison with the calculated composition of the lava in a holocrystalline condition given below, practically all the quartz and 85 per cent of the orthoclase and albite are in the groundmass, which is estimated to consist of equal parts of glass and microcrystalline material.

Chemical composition.—The analysis of the type specimen (1866) from the summit of Sugarloaf Hill gave the following results:

Chemical analyses of biotite rhyolite of Sugarloaf Hill and type rhyolite.

	1		2
	Per cent.	Molecular ratio.	
SiO_2	74.02	1.234	73.5
Al_2O_3	13.20	.129	13.5
Fe_2O_3	.75 / [a] .50	.005	1.4
FeO	.29 / [a] .52	.004	1.0
MgO	.06	.002	.3
CaO	.56	.010	.6
Na_2O	4.18	.067	3.7
K_2O	4.82	.051	5.1
H_2O+	1.86		.7
H_2O-			
TiO_2	.02		.3
P_2O_5			.1
Cl	Trace.		
MnO	Trace.		.1
	99.76		100.3

[a] Adjusted value for fresh rock.

1. Biotite rhyolite, Sugarloaf Hill, San Franciscan volcanic field, Arizona. S. H. Clapp, analyst.
2. Type rhyolite.

The rhyolite of Sugarloaf Hill is a typical rhyolite. The low iron and magnesia show the presence of a very small quantity of dark minerals, as may be seen from the mineral composition.

Mineral composition.—The complete mineral composition, calculated from the chemical composition and micrometric analysis, is as follows:

Modes of rhyolite of Sugarloaf Hill and of type rhyolite.

	1	2	3
Quartz	30.1	31.4	−1.3
Orthoclase	29.3	28.2	+1.1
Albite	33.0	28.2	+4.8
Oligoclase (Ab_4An_1)	4.0	5.0	−1.0
Biotite	1.1	5.6	−5.1 (Biotite and Magnetite)
Magnetite	.6	1.2	
Water	1.8	.6	....
	99.9	100.2	+5.9 −7.4

1, Mode of rhyolite of Sugarloaf Hill; 2, mode of type rhyolite; 3, departures of mode 1 from mode 2.

The amount of biotite in the rhyolite of Sugarloaf Hill is obtained by assuming that all the magnesia is in that mineral and assigning the other oxides in conventional proportions. The rest of the iron then forms magnetite. As both the biotite and magnetite in the rock are slightly altered, ferric iron is too high and ferrous iron too low. The adjusted values for the fresh rock are Fe_2O_3 0.50 per cent and FeO 0.52 per cent. Part of the lime, as anorthite, is put in orthoclase and albite. If it were all in anorthite the amount of plagioclase would be much larger than is shown by the thin section. The remaining soda and potash enter orthoclase and albite; the excess silica forms quartz. The lava is made up almost wholly of salic minerals, as the calfemic members form less than 2 per cent of the total. As compared with the type rhyolite, albite is slightly higher and calfemic minerals lower. The plus and minus departures are not equal because the summations of the two modes and the amounts of water are not the same.

The composition of the biotite, as adjusted from the chemical and micrometric analyses, is as follows:

Composition of biotite in rhyolite of Sugarloaf Hill.

SiO_2	33.4	K_2O	8.4
Al_2O_3	18.5	TiO_2	1.8
Fe_2O_3	3.7		100.0
FeO	27.0		
MgO	7.4		

Ferrous iron is much higher and magnesia lower than usual, but this is necessary in order to have the calculated mode agree with that indicated by the thin section. The composition is similar to that of several biotites given in Dana's Mineralogy and especially close to the biotite of Miask.

No. 2. BIOTITE-SODA GRANITE PORPHYRY (KALLERUDOSE, I.4.1.4).

Occurrence.—Biotite-soda granite porphyry forms the Marble Hill laccolith and is found only at the central peak.

Megascopic characters.—The rock is light bluish gray in color and has a uniform aphanitic texture. Phenocrysts of prismatic feldspar and anhedral quartz (average length, 3 millimeters; maximum, 8 millimeters) form about 5 per cent of the rock; biotite 1 millimeter in maximum length constitutes 3 per cent.

Microscopic characters.—The groundmass of the rock is holocrystalline and has a fairly uniform grain averaging 0.05 millimeter. It is composed of prismoids of orthoclase, microperthite, and anhedral and interstitial quartz, with a sprinkling of dark specks generally square in outline but showing no metallic luster. Plagioclase of the composition Ab_4An_3, quartz, and biotite occur as phenocrysts, forming about 15 per cent of the rock. As no striated feldspar is to be seen in the groundmass, it is probable that all the plagioclase is in the form of phenocrysts, which occur as idiomorphic prismoids, except where they are clustered. The biotite is also in idiomorphic crystals, but the quartz is in rounded or skeleton forms. Magnetite and in a few crystals zircon and hornblende occur as accessories.

Chemical composition.—The analysis of a perfectly fresh specimen (1883) from the summit of the hill gave the following results:

Chemical analysis of biotite-soda granite porphyry of Marble Hill.

	1		2
	Per cent.	Molecular ratio.	
SiO_2	74.23	1.237	73.5
Al_2O_3	13.65	.134	13.5
Fe_2O_3	.84	.005	1.4
FeO	1.04	.014	1.0
MgO	.23	.006	.3
CaO	.75	.013	.6
Na_2O	4.87	.078	3.7
K_2O	3.96	.042	5.1
H_2O+	.19		.7
H_2O-			
CO_2	None.		
TiO_2	.08	.001	.3
ZrO_2	Present.		
P_2O_5	Undet.		.1
Cl	Trace.		
MnO	Trace.		.1
	99.84		100.3

1. Biotite-soda granite porphyry, Marble Hill, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.56.
2. Type granite-rhyolite.

The rock of Marble Hill is classified as a soda granite porphyry. The ratio of potash to soda is 1 : 1.9, compared with 1 : 1 in the type rhyolite. The rock differs from the soda rhyolites of San Francisco Mountain and Mount Sitgreaves in having the molecular sum of the alkalies less than that of alumina.

Mineral composition.—The mineral composition, as calculated from the chemical analysis, is as follows:

Modes of granite porphyry of Marble Hill and of type granite-rhyolite.

	1	2	3
Quartz	29.5	31.4	−1.9
Orthoclase	21.8	28.2	−6.4
Albite	36.1	28.2	+7.9
Andesine (Ab_4An_3)	8.4		+3.4
Oligoclase (Ab_4An_1)		5.0	
Biotite	3.1	5.6	−2.8 (Biotite and Magnetite)
Magnetite	.9	1.2	
Water		.6	
	99.8	100.2	+11.3 −11.1

1, Mode of granite porphyry of Marble Hill; 2, mode of type granite-rhyolite; 3, departures of mode 1 from mode 2.

The magnetite in the porphyry of Marble Hill is estimated from thin sections to take 4 molecules each of ferric and ferrous iron. The remaining iron, all the magnesia and titania, and part of the water are put into biotite. Potash is added in the proportion to magnesia and ferrous iron of 1 : 5.3; alumina to potash, 1 : 1.3; and silica to potash, 6 : 1. If alumina and potash are present in the biotite in the proportion of 1 : 1.3, then just sufficient alumina is left to combine with the rest of the potash, soda, and lime in the ratio of 1 : 1 to form the feldspars.

The excess silica is calculated as quartz. The amount of microperthite is not determinable on account of the fine grain of the rock, so that it is necessary to give orthoclase and albite in bulk amounts. As compared with the type rhyolite, orthoclase is low and albite high, which expresses the soda-rich character of the rock. Otherwise the departures are slight.

The composition of the biotite used in calculating the mode is as follows:

Composition of biotite in granite porphyry of Marble Hill.

SiO_2	35.3	K_2O	9.2
Al_2O_3	13.0	H_2O	3.0
Fe_2O_3	5.3	TiO_2	2.6
FeO	23.6		
MgO	8.0		100.0

The ferrous iron is distinctly high and magnesia low, as would be expected from the chemical analysis of the rock. The composition in general is similar to several analyses given in Dana's Mineralogy and is especially close to No. 22 of the biotite from Miask. The result appears reasonably satisfactory in view of the assumptions made in regard to the composition and the fact that errors in the rock analysis would be greatly magnified because of the small amount of the mineral.

No. 3. BIOTITE-SODA RHYOLITE (KALLERUDOSE, I.4.1.4).

Occurrence.—The biotite-soda rhyolite here described forms Sitgreaves Peak and three small cones just east of it.

Megascopic characters.—The lava is a typical rhyolite. It ranges in color from light lavender and lilac through pearl-gray, light or dark gray, and slate to black. It varies from compact lithoidal through spherulitic varieties to porous and compact glasses. The dark colors are commonly associated with the glasses. It is, in general, nonporphyritic.

Microscopic characters.—In thin sections all the lavas, with two exceptions, are seen to be glasses. They are very fresh and only one, the lithoidal lava of cone A (fig. 14, p. 67), shows any sign of devitrification.

Idiomorphic phenocrysts of soda orthoclase, a few of oligoclase (Ab_4An_1), and corroded quartz in crystals up to 5 millimeters long, constitute in most specimens not over 5 per cent of the rock, but in a few reach a maximum of 20 per cent. Some of the larger orthoclase crystals are graphically intergrown with quartz. The groundmass contains numerous submicroscopic black crystals, averaging perhaps 0.005 millimeters in diameter, which form the nuclei of radiating growths of trichites. The dark mineral, so far as can be judged, is predominantly biotite; at least it is so in the lava of cone B. Without exception it is much altered, some of it completely so, to a black opaque mass. Zircon and a greenish hornblende occur in very small amounts.

Of the two specimens which are not glasses one is a drab-colored lava from the northeast slope of the mountain. It has a hypomicrocrystalline groundmass composed predominantly of lath-shaped feldspars which are plainly arranged in lines of flow. The second specimen has a holomicrocrystalline groundmass composed principally of lath-shaped feldspars but in part of stouter feldspars; it probably represents a core or dike rock. Both these specimens are differentiated from the other lavas by numerous roughly circular patches of quartz of indefinite outline. These quartz areas are invariably filled with minute feldspar crystals diversely arranged and thus have a micropoikilitic structure. It is supposed that these areas, like those seen in rather similar specimens found at Kendrick Peak and Slate Mountain, are the result of secondary enrichment by fumarole action.

Chemical composition.—The analysis of the perfectly fresh obsidian (2202) of cone A is as follows:

Chemical analyses of biotite-soda rhyolite of Sitgreaves Peak and type rhyolite.

	1		2
	Per cent.	Molecular ratio.	
SiO_2	74.93	1.249	73.5
Al_2O_3	13.11	.129	13.5
Fe_2O_3	.51	.003	1.4
FeO	.77	.011	1.0
MgO	.23	.006	.3
CaO	.30	.005	.6
Na_2O	5.64	.091	3.7
K_2O	4.28	.046	5.1
H_2O+	.28		.7
H_2O-	.04		
CO_2	None.		
TiO_2	.07	.001	.3
ZrO_2	Present.		
P_2O_5	Undet.		.1
Cl	Trace.		
F	Undet.		
MnO	Trace.		.1
	100.16		100.3

1. Biotite-soda rhyolite. Sitgreaves Peak, cone A, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.37.
2. Type rhyolite.

Comparison with the type shows the lava to be a typical soda rhyolite in which the ratio of potash to soda is 1 : 2. The sum of the alkalies exceeds the alumina by 8 molecules, which would indicate the possibility of the formation of an iron-soda pyroxene or amphibole, as in the riebeckite rocks of San Francisco Mountain. However, for 8 molecules of soda there are but 3 molecules of ferric iron, and the actual difference is even greater, as some of the alumina goes into anorthite, which with albite forms oligoclase. Unless, therefore, there are errors of more than usual magnitude in the analysis, a mineral of the composition of riebeckite apparently would not form.

Mineral composition.—The exact mineral composition is uncertain because the character of the calfemic mineral is in doubt. The actual errors in the mode can not be great, however, as this mineral is present in small amount. If biotite is supposed to be present there is insufficient alumina to satisfy the alkalies and lime in forming the feldspars. If an iron-soda mineral is present a composition for it can not be obtained which agrees well with any known mineral. It seems preferable, however, to consider the iron-soda mineral present. It is arbitrarily composed of all the ferric and ferrous iron, magnesia, and titania, 2 molecules of lime, and 10 of soda, to which an equal number of molecules of silica are added. Alumina is then equal to the rest of the alkalies and lime. The composition thus obtained is approximated by a mixture of riebeckite and barkevikite. The mineral composition of the lava is as follows:

Modes of rhyolite of Sitgreaves Peak and of type rhyolite.

	1	2	3
Quartz	26.9	31.4	—4.5
Orthoclase	25.6	28.2	—2.6
Albite	39.2	28.2	+11.0
Oligoclase (Ab_4An_1)	4.0	5.0	—1.0
Calfemic minerals	4.2		
Biotite		5.6	—2.6 (Biotite and Magnetite)
Magnetite		1.2	
Water	.3	.6	
	100.2	100.2	+11.0 —10.7

1, Mode of rhyolite of Sitgreaves Peak; 2, mode of type rhyolite; 3, departures of mode 1 from mode 2.

The above result fairly represents the mineral composition of the lava in a holocrystalline state. The amount of the calfemic component can be but slightly changed, whatever method of calculation is used. Quartz, orthoclase, and albite form over 90 per cent of the mode, indicating its predominantly salic character. As shown in column 3 of the table, the soda-rich character of the lava is expressed by the high albite; otherwise the departures from the type rhyolite are slight.

No. 4. RIEBECKITE-SODA RHYOLITE (KALLERUDOSE, I.4.1.4).

Occurrence.—Riebeckite-soda rhyolite is found only on San Francisco Mountain in the saddle between Agassiz and Fremont peaks.

Megascopic characters.—It is a typical rhyolite and occurs principally in banded light-gray and red spherulitic or mottled gray and salmon lithoidal varieties, with a small proportion of brilliant black obsidian. The spherulites are in all sizes from a fraction of a millimeter to 5 millimeters in diameter, the average being not over 1 millimeter; the lithophysæ are much less numerous though somewhat larger than the spherulites. The flow lines in the lava are shown in the spherulitic and lithoidal varieties by alternating thin bands of different colors and in the obsidian by parting planes produced by very thin interrupted layers of lithophysæ. Phenocrysts of an unstriated prismoidal feldspar occur very sparingly in all three varieties, ranging in length from 1 to 9 millimeters, with the average at 3 millimeters.

Microscopic characters.—In thin section the lava shows typical rhyolite textures ranging from an almost perfect glass through cryptocrystalline into microcrystalline varieties. The spherulites occur in a cryptocrystalline groundmass and have the ordinary uniform radial or microcrystalline structures. Both forms not uncommonly have about them a younger radial growth of crystals. Phenocrysts are extremely rare and consist almost entirely of orthoclase. Apatite and zircon are present in insignificant amounts and magnetite is absent.

Chemical composition.—An analysis of the black obsidian (1822) gave the following results:

Chemical analysis of riebeckite-soda rhyolite of San Francisco Mountain and related rocks.

	1		2	3
	Per cent.	Molecular ratio.		
SiO_2	74.01	1.234	74.76	73.5
Al_2O_3	13.08	.128	11.60	13.5
Fe_2O_3	1.38	.009	3.50	1.4
FeO	1.21	.017	.19	1.0
MgO	Trace.		.18	.3
CaO	.13	.002	.07	.6
Na_2O	5.78	.093	4.35	3.7
K_2O	4.31	.046	4.92	5.1
H_2O+	.16		.64	.7
H_2O-	.10			
CO_2	None.			
TiO_2	.11	.001		.3
ZrO_2	Pres.			
P_2O_5	Trace.			.1
Cl	Trace.			
F	Undet.			
MnO	Trace.			.1
Li_2O	Trace.			
	100.27		100.21	100.3

1. Riebeckite-soda rhyolite, San Francisco Mountain, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.38.
2. Comendite, Comende, San Pietro Island, Sardinia (type locality). M. Dittrich, analyst. (Rosenbusch, H., Elemente der Gesteinslehre, 1898, p. 257.)
3. Type rhyolite.

The lava has the composition of a typical rhyolite except that it is rich in soda, the ratio of potash to soda being 1:2, as compared with 1:1 in the type rhyolite. The sum of the alkalies is greater than the alumina, which would permit soda to combine with iron and silica to form an iron-soda pyroxene or amphibole. The lava resembles in a general way the comendite from Sardinia, the analysis of which is given in the table. The comendite, however, is not noticeably rich in alkalies and the ratio of potash to soda is about that of the type rhyolite. The excess of soda, which goes into the iron-soda mineral, is due in the comendite to low alumina.

Mineral composition.—The mode calculates out as follows:

Modes of soda rhyolite of San Francisco Mountain and of type rhyolite.

	1	2	3
Quartz	24.5	31.4	− 6.9
Orthoclase	25.6	28.2	− 2.6
Albite	43.0	28.2	+14.8
Oligoclase ($Ab_4 An_1$)	....	5.0	− 5.0
Riebeckite	6.9	....	
Biotite	....	5.6	+ 0.1
Magnetite	....	1.2	
Water	.2	.6	....
	100.2	100.2	+14.9 −14.5

1, Mode of soda rhyolite of San Francisco Mountain; 2, mode of type rhyolite; 3, departures of mode 1 from mode 2.

The mode of the lava of San Francisco Mountain is obtained by assigning to potash sufficient alumina and silica to form orthoclase, the rest of the alumina with proper amounts of soda and silica forming albite. All the ferric iron is combined with the remaining soda and silica to form the molecule $NaFe'''Si_2O_6$, and to this are added the ferrous iron and lime, with silica and the titania in the proportion of 1:1. The excess silica is considered as quartz. The composition of the calfemic mineral thus obtained is: SiO_2, 49.1; TiO_2, 1.6; Fe_2O_3, 20.1; FeO, 17.8; CaO, 1.9; Na_2O, 9.5; total, 100. This is clearly a riebeckite in which $2NaFe'''Si_2O_6$ and $FeSiO_3$ are present in the proportion 1:2.2. As this lava is a glass, nothing is actually known in regard to its mineral composition. The calfemic mineral might be acmite, as that is much commoner than riebeckite in effusive rocks. However, riebeckite occurs in the intrusive equivalent of the rhyolite, which is next described, and may form in the rhyolite. As compared with the type rhyolite, the lava of San Francisco Mountain has high albite and no plagioclase. The calfemic mineral is riebeckite instead of biotite, which produces an abnormal (uncommon) mode. The lava is classified as a riebeckite-soda rhyolite.

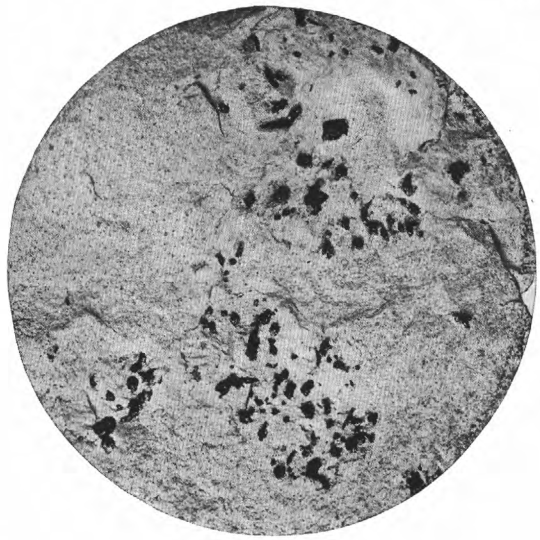
The mineral composition of the comendite from the type locality is too complex to permit the calculation of the mode without knowledge of the relative amounts of the several dark minerals which occur in the lava. The high ferric iron in the analysis of the lava shows that ægirite or riebeckite must be the principal calfemic component. If the small amount of magnetite described as present is as great as 0.6 per cent it would take all the ferrous iron given in the rock analysis, thus leaving none for the ægirite or riebeckite and an amphibole, which contains 27.7 per cent of ferrous iron.[1] The reason for the discrepancy is not evident, although it may be noted that if the values of ferric and ferrous iron were transposed in the analysis of the amphibole mineral above cited, its composition would be remarkably similar to that of ægirite, which is described as the prevailing calfemic constituent.

No. 5. RIEBECKITE-SODA GRANITE PORPHYRY (KALLERUDOSE, I.4.1.4).

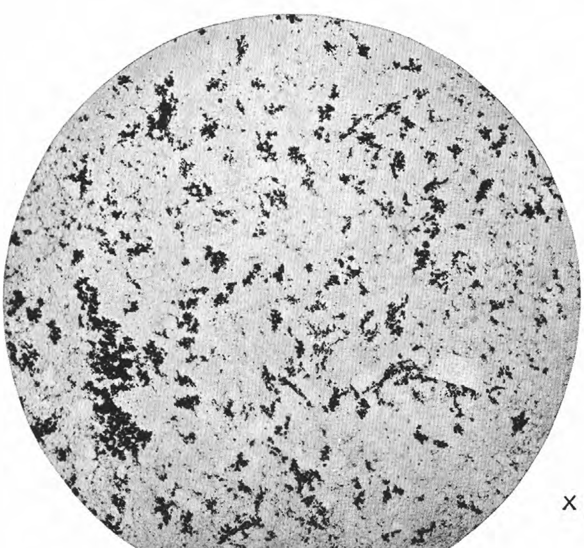
Occurrence.—Riebeckite-soda granite porphyry is found only on the inner (northwest) slope of Fremont Peak, San Francisco Mountain, as a mass of loose blocks marking the position of the conduit through which the magma escaped.

Megascopic characters.—The rock occurs in two distinct varieties. The normal variety is uniformly compact, of bluish to pearl-gray color, speckled with microscopic black crystals. It has a cryptocrystalline texture and contains about 1 per cent of unstriated feldspar phenocrysts which range from 2 to 8 millimeters in length. A banded structure on a fine scale is common, being produced by the dark mineral gathered in more or less distinct layers; a microgranitoid structure occurs less commonly. The abnormal variety is similar to the normal, except that it contains numerous segregated groups of the dark mineral embedded in a white matrix (Pl. XIII, *A*). In cross section they appear as narrow white bands through the middle of which is another very much narrower black band. The boundary between the white matrix and surrounding rock is sharply defined. These segregations vary considerably in shape and size, but all are exceedingly thin. Elongated forms, roughly eliptical in outline, are rather

[1] Rosenbusch, H., Elemente der Gesteinslehre, 1898, p. 258.



A



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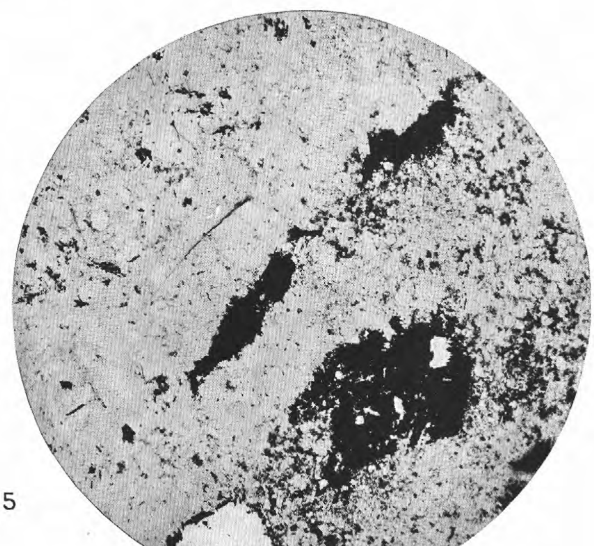


B *C*

GRANITE PORPHYRY OF SAN FRANCISCO MOUNTAIN.

A, Variety containing segregated areas (natural size); *B*, normal variety; *C*, abnormal variety.

common and range from less than 1 centimeter to 10 centimeters in longer diameter. The larger segregations are rare, so that the average length is about 3 centimeters and the thickness not generally over 3 millimeters, or one-tenth the length. The segregations most commonly lie parallel to the banding of the rock, but many of them occur as veinlets cutting across the flow structure, thus clearly indicating that they were formed after the consolidation of the magma. The dark mineral is an amphibole, occurring either in stout prisms or more commonly in thin tabular crystals developed parallel to *a* (100). They are of all sizes from 1 to 6 millimeters, but most commonly about 2 millimeters long.

Microscopic characters.—The normal variety has a compact fine-grained holocrystalline groundmass in which the crystals are xenomorphically developed. It consists essentially of soda orthoclase, microperthite, and quartz, with scattered swarms of small dark-blue and dark-brown minerals (Pl. XIII, *B*). Zircon is present in very small amount both as separate crystals and as minute inclusions in quartz. The first mineral to separate out was soda orthoclase in prismatic crystals about 3 millimeters in length, which constitute 1 per cent of the rock. Then came a second crystallization of soda orthoclase in idiomorphic prismoids from 0.1 to 0.2 millimeter in length, and also of a portion of the quartz in anhedral individuals averaging 0.07 millimeter in length. This was followed by the crystallization of the rest of the feldspars (mostly as microperthite), quartz, and also the dark minerals; these form the groundmass of the rock. The quartz and amphibole crystals average 0.015 millimeter in diameter, the feldspar 0.02 millimeter in length. The order of crystallization in the groundmass is uncertain because of the small size of the crystals and their consequent overlapping. In many specimens the minerals of what is called the groundmass appear to have crystallized simultaneously. Part of the amphibole separated out first, as it is commonly grouped about the feldspar and quartz of the second stage of crystallization. The amphibole forms clusters of tabular and prismatic crystals, partly of idiomorphic, partly of xenomorphic outline. The blue amphibole is strongly pleochroic, the color parallel to $\dot{c}$ being a dark blue or bluish green. The brown variety is so deeply stained that the pleochroic colors are difficult to determine; they can occasionally be distinguished as very dark and light brown in positions oblique to the $\dot{c}$ axis. The small size of the crystals makes it impossible to determine other optical properties. Probably the minerals are the same as occur in the segregations, namely, riebeckite and ænigmatite.

In thin section (Pl. XIII, *C*) the abnormal variety of the rock is seen to be the same as the normal type, except for the segregations, in which there has been a concentration of the amphiboles and an addition of certain other minerals. The white matrix of the segregations is the same as the groundmass of the normal variety, as regards feldspar and quartz, and the boundaries of the segregations can be recognized only by the disappearance of the clusters of minute amphibole crystals and their replacement by larger individuals.

The same two amphiboles seen in the normal variety of rocks are present in the segregations and the blue variety greatly predominates over the brown. They tend to develop in stout prismatic crystals, the largest 1 by 1.5 millimeters in size. The prismatic zone in some crystals is well developed, but terminal faces are invariably lacking and the crystals generally fray out into the surrounding groundmass. Basal sections of the blue mineral show the characteristic amphibole cleavage angle. Ten determinations of the angle of extinction in sections parallel to 010, as judged by the cleavage and pleochroism, gave values ranging from 2° to 8°, with the average at 5°. The index of refraction is 1.68.

The relation of the axes of elasticity to the crystallographic axes is as follows: In sections parallel to 100 $x=c$ and $z=a$; in sections parallel to 010 $x=c$ and $z=b$; in sections parallel to 001 $x=a$ and $z=b$. Therefore x lies near c, y is near a, and z coincides with b. The axis of greatest elasticity, then, lies in the plane of symmetry, and that of least elasticity is parallel to b, so that the plane of the optic axes is normal to the plane of symmetry. This is evidently the common relation as it occurs in all properly oriented sections. The dispersion of the axes of elasticity is pronounced and changes from brown to green on either side of the extinction position.

The pleochroism is very marked as well as somewhat variable. The colors are: *x*, very generally deep green or bluish green, occasionally deep blue; *y*, light olive brown or bluish gray; *z*, dark blue or blue gray.

The above characters are sufficient to show that the mineral is riebeckite, possibly containing some proportion of the arfvedsonite molecule. The only unusual feature is the location of the plane of the optic axes perpendicular to the plane of symmetry. This relation, however, has been observed by Fruedenberg [1] in the periphery of an iron-rich amphibole, in whose center $y=b$.

The brown amphibole is so deeply pigmented that it is practically opaque, consequently its character can not well be determined. The angle of extinction is inclined about 40° to *c* and the dispersion of the axes of elasticity is weak. The pleochroism is from dark to light brown and is also inclined 40° to the cleavage in prismatic sections. If the section in which these features are seen is parallel to *b*, the mineral may be safely identified as ænigmatite.

Zircon is noticeably abundant in the segregations, although it is rarely detected in the normal rock. It occurs in idiomorphic but more commonly anhedral crystals up to 0.4 millimeters in length, and wherever the relation is most certainly determinable, it crystallized before the riebeckite. Fluorite as small pink cubes and fragments occurs as inclusions in some of the zircon. Topaz is also found in the segregations in small amount. It builds imperfect crystals up to 0.4 millimeter in length. The index of refraction is slightly lower than that of the hornblende (1.68) and the birefringence lies between 0.009 and 0.011, depending on whether the thickness of the section is measured from the interference colors of quartz or of zircon. In a section of low interference color showing no cleavage a positive interference figure appears, and in prismatic sections an optic axis lies not far outside the field. In addition to the above-named minerals a single small crystal of a green spinel was observed.

In some of the segregated areas there is a greater abundance of quartz in idiomorphic crystals than in the groundmass, which apparently represents a crystallization of this mineral contemporaneous with the formation of the amphibole, zircon, and topaz.

The secondary origin of the amphibole and associated minerals of the segregations can be more clearly seen microscopically than megascopically. Veinlets, most commonly filled with riebeckite or marked by altered feldspars, may be traced through the rock in various directions into the segregated areas and from one area to another.

Origin of the abnormal variety.—All the facts indicate that the abnormal variety resulted from pneumatolytic action on the normal variety after it had solidified in the chimney of the volcano. The banded structure of the rock most probably represents vertical flow lines, such as are found in the dacite core of Bill Williams Mountain, and also at Mount Johnson in Canada,[2] although this can not be proved, as no rock was observed in place. The vapors would presumably rise along these vertical structure planes, as they would be the paths of least resistance. This would account for the elongated forms of the segregations and the fact that they commonly lie parallel to the banding of the rock.

The temperature of the escaping vapors need not have been very high, although the pneumatolytic action which caused the segregation of the amphibole and the formation of the associated minerals presumably occurred soon after the solidification of the rock and represented the final phase of this particular stage of volcanic activity in San Francisco Mountain. The upper limit may be set near the melting point of orthoclase or albite, approximately 1,000° C., as these minerals have undergone no alteration in form, although they have been somewhat locally decomposed. At some places it could not have exceeded 800° C.—the melting point of quartz. The melting point of the amphibole is about 950° C., but that of zircon is 1,760° C. The crystallization of the zircon at a temperature so far below its melting point shows that the formation of the minerals was in general according to the laws of solution. The lower limit of temperature, therefore, may have been considerably less than the upper limit of 800° to 1,000° C.

A comparison of the abnormal with the normal variety of rock shows that both carry the same amount of the amphibole minerals in the unsegregated portion. In the segregated areas of the abnormal variety, however, there is an increase in the amount of amphibole, zircon,

[1] Rosenbusch, H., Mikroskopische Physiographie der petrographischen wichtigen Mineralien, 1905, p. 247.
[2] Adams, F. D., The Monteregian Hills, a Canadian petrographical province: Jour. Geology, vol. 11, 1903, p. 278.

and possibly quartz, and also the addition of topaz. This evidently indicates a secondary enrichment with respect to zirconium, fluorine, iron, sodium, aluminum, silicon, and oxygen.

The locality at which the specimens were collected is not more than 2,000 feet below the point at which the lava escaped, as calculated from cross section A–A′ of Plate VI (p. 40). The pressure at this horizon may therefore be roughly estimated as equal to the weight of the superincumbent column of rock. It figures out as 2,300 pounds, or 150 atmospheres, to the square inch. This may be considered the minimum, as several factors which would tend to increase it somewhat are disregarded. It may be said, however, that the pneumatolytic action probably took place under distinctly low pressure and at low temperatures, such as are easily within the range of laboratory experiment.

Chemical composition.—The analysis of the perfectly fresh normal variety (1839) is given below:

Chemical analyses of riebeckite-soda granite porphyry of San Francisco Mountain and related rocks.

	1		2	3
	Per cent.	Molecular ratio.		
SiO_2	74.19	1.237	73.35	73.5
Al_2O_3	12.85	.126	14.38	13.5
Fe_2O_3	1.60	.010	1.96	1.4
FeO	.98	.014	.34	1.0
MgO	.11	.003	.09	.3
CaO	.12	.002	.26	.6
Na_2O	5.86	.094	4.33	3.7
K_2O	3.98	.042	5.66	5.1
H_2O+	.10			.7
H_2O-	.16			
CO_2	None.			
TiO_2	.09	.001		.3
ZrO_2	Present.			
P_2O_5	Trace.			.1
Cl	Trace.			
F	Undet.			
MnO	Trace.			.1
BaO	Trace.			
Li_2O	Trace.			
	100.04		100.37	100.3

1. Riebeckite-soda granite porphyry, San Francisco Mountain, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.66.
2. Paisanite, Mosquez Canyon, Apache Mountains, trans-Pecos Texas (type locality). A. Osann, analyst. (Min. pet. Mitt., vol. 15, 1895, p. 439.)
3. Type rhyolite.

The rock is a soda-rich granite porphyry in which the ratio of potash to soda is 1:2.2. The molecular sum of the alkalies is 0.010 greater than the alumina. This equals the number of molecules of ferric iron and indicates that the soda is combined with it in the proportion of 1:1. The analysis of paisanite from the type locality is given in column 2. It differs from the San Franciscan rock in its higher alumina and in its ratio of potash to soda of 1:1.2. The sum of the alkalies is less than alumina by 11 molecules. Osann states [1] that the riebeckite is a relatively younger crystallization of the magma and that the building of the feldspars of the groundmass came before it in part.

Mineral composition.—The complete mineral composition, as calculated from the chemical analysis and also as measured by the Rosiwal method, is as follows:

Modes of riebeckite-soda granite porphyry of San Francisco Mountain.

	Calculated.	Measured.	Average size of crystals (millimeters).
Quartz	25.4	24.8	0.02
Orthoclase	23.4 } 67.4	67.9	.03
Albite	44.0 }		
Riebeckite	7.0	7.3	.015
	99.8	100.0	.025

[1] Beiträge zur Geologie und Petrographie der Apache (Davis) Mountains, West-Texas: Min. pet. Mitt., vol. 15, 1895, p. 435.

The calculated result is obtained by combining the ferric iron with soda and silica in the ratio 1:1:4 and adding the ferrous iron, magnesia, and lime with silica, including titania, in the proportion of 1:1, to form the amphibole. The rest of the soda goes into albite, the potash into orthoclase, and the excess of silica forms quartz. The soda-rich character of the rock is shown by the large amount of albite, which constitutes nearly half of it. The soda, however, is not wholly in albite; part of it occurs in soda orthoclase and microperthite. The agreement between the calculated and measured results is highly satisfactory and shows that the Rosiwal method may be successfully applied to very fine-grained rocks. In this rock the average grain is 0.025 millimeter, or about the thickness of the thin section; it is presumably the smallest grain that can be measured by this method, as the overlapping of crystals in a finer-grained rock would cause serious errors.

Composition of the riebeckite.—The composition of the riebeckite from the rhyolite and granite porphyry of San Francisco Mountain and the paisanite of the Apache Mountains, Tex., as calculated from the chemical composition of the rocks, and also the analysis of the mineral itself from the type locality in Socotra, Indian Ocean, are given in the following table. It should be said that corrected values for ferric and ferrous iron of 1.35 and 0.89 per cent, respectively, have been used in calculating the composition of the riebeckite of the paisanite. Osann speaks of this mineral as being slightly altered and the analyzed values of ferric and ferrous iron show that this is so. The amounts of ferric and ferrous iron have therefore been changed to conform to the average ratio 1:1.5 for riebeckite-bearing rocks similar to paisanite.

Chemical analyses of riebeckite.

	1	2	3	4
SiO_2	49.1	49.3	49.5	49.6
TiO_2	1.6	1.3	.....	.....
Fe_2O_3	20.1	23.0	23.2	29.5
FeO	17.8	14.0	15.3	9.5
(Fe_2O_3+FeO)	(37.9)	(37.0)	(38.5)	(39.0)
MgO	.....	1.6	1.5	.3
CaO	1.9	1.7	1.9	2.0
Na_2O	9.5	8.9	8.6	9.5
	100.0	100.0	100.0	100.4

1. From rhyolite, San Francisco Mountain.
2. From granite porphyry, San Francisco Mountain.
3. From paisanite, Apache Mountains, Texas.
4. From type locality, Socotra, Indian Ocean. An average of two analyses. MnO combined with FeO and K_2O with Na_2O. Dana's Mineralogy, 1892, p. 400.

The first three analyses show a remarkably close agreement with the analyzed composition given in column 4, when it is considered that they have been indirectly derived from the rock analyses and that reibeckite is a mixture of $m\text{NaFe}'''(\text{SiO}_3)_2 + n\text{FeSiO}_3$. The amounts of the several oxides, except the silica, have been derived from the rock analyses. The agreement for the silica is in part due to the assumption that it is combined with the bases in the accepted riebeckite proportions. The similarity between the riebeckite from San Francisco Mountain and that from the Apache Mountains is very close and in both $\text{NaFe}''' (\text{SiO}_3)_2 : \text{FeSiO}_3 :: 1:2$, whereas in the Socotra mineral the ratio is 1:1. The results show that as much confidence may be placed in the calculation of the composition of a mineral under favorable conditions from a rock analysis as in an analysis of the individual mineral itself.

THE DACITIC LAVAS.

OCCURRENCE AND GENERAL CHARACTER.

Dacitic lavas occur at San Francisco Mountain, Kendrick and O'Leary peaks, and Bill Williams, Mormon, and Elden mountains. They are the most widely spread lavas of the second general period of eruption. As previously explained, the type dacite is midway between the type rhyolite and the type andesite, a fact which should be borne in mind in reading the following descriptions. The dacitic lavas are intermediate between the rhyolites and andesites of the region. Their most distinctive chemical feature is the predominance of soda over potash, which gives them a trachytic cast. They all have similar textures and are clearly related, except the biotite dacites of Kendrick and of O'Leary peaks. These last have typical rhyolitic textures, as well as certain mineralogic characters, which point to their relationship with the rhyolites of the region. Their more basic composition, as compared with the rhyolites, is a result of regional differentiation. The normal calfemic mineral of the dacites is hornblende or hypersthene, with some augite, either individually or together. The calculated modes of the lavas show that they consist predominantly of quartz, orthoclase, albite, and andesine. They all show a more or less well-marked tendency to form massive flows, a feature that distinguishes them from all other lavas in the field. This mode of occurrence is interpreted as indicating a rather high degree of viscosity at the time of eruption, a character which was most pronounced in the lava of Elden Mountain.

No. 6. BIOTITE DACITE OF KENDRICK PEAK (LASSENOSE, I.4.2.4).

Occurrence.—Biotite dacite forms the greater part of the mass of Kendrick Peak. It is exposed in the upper part of the cone, above an elevation of 10,000 feet, and covers about 9 square miles northwest of the mountain.

Megascopic characters.—The lava has the appearance of a typical rhyolite and would be so classified in the field. It ranges from very light-gray, light-lilac or pink felsites through similarly colored spherulitic varieties, many of which contain lithophysæ, to a brilliant greenish-black glass. The coarser spherulitic lavas are nearly free from phenocrysts, but the more uniform and finer-grained spherulitic varieties, where the spherulites average less than 1 millimeter in diameter, contain a very small percentage of feldspar and biotite crystals. The felsitic lavas in part contain similar phenocrysts, in part are free from them. Only feldspar is seen in the obsidian.

Microscopic characters.—All varieties have predominantly hyaline or cryptocrystalline textures. In the most coarsely crystallized specimens the feldspars of the groundmass average about 0.01 by 0.05 millimeter, and the biotite, pyroxene, and magnetite, which are present in small amount, are still smaller in size.

Oligoclase phenocrysts of the composition Ab_5An_3, generally as stout idiomorphic prisms not over 2 millimeters in length, constitute at a maximum 20 per cent of the rock. Biotite is the prevailing dark mineral and occurs in fresh idiomorphic crystals, few of which are over 1 millimeter in length. Hypersthene occurs in small fresh crystals in some flows. Hornblende phenocrysts are present as a rule, but only in very small amount.

The lava as seen in thin section is clearly rhyolitic in character and would so be classified, although the 20 per cent of oligoclase phenocrysts indicates a higher lime content than is found in the type rock.

Crystallinity.—Practically all degrees of crystallinity from holohyaline to holocryptocrystalline, or possibly microcrystalline, are present. Micrometric analyses of the type specimen (2151) and of a more glassy variety (2149) may be given to illustrate intermediate stages.

Micrometric analyses of biotite dacite of Kendrick Peak.

	Percentage by weight.				Average size of crystals (millimeters.)	
	Type specimen 2151.		Specimen 2149.		Type Specimen 2151.	Specimen 2149.
Glass	6.6	95.6	24.5	95.3	....	....
Spherulites	70.7		55.9		....	....
Oligoclase (Ab_5An_3)	18.3		14.9		0.44	0.49
Biotite and hornblende	2.5	4.4	4.5	4.7	.16	.17
Hypersthene	1.3		.....		.11	....
Magnetite	.6		.2		.05	.04
	100.0		100.0		....	....

The groundmass, which consists of glass and spherulites, constitutes in each specimen about three-quarters of the rock, and feldspar phenocrysts are over three times as abundant as calfemic minerals. The amount of the latter given in the table does not represent the total for either specimen because some of these minerals occur in the groundmass. The principal difference between the two specimens is in the relative amounts of glass and spherulites, the former crystallizing into the latter. The average size of the phenocrysts is the same in both specimens and is thus independent of the condition of the groundmass.

Chemical composition.—The analysis of the fresh type specimen (2151), from the northwest slope of the cone, gave the following results:

Chemical analyses of biotite dacite from Kendrick Peak and related rocks.

	1		2	3
	Per cent.	Molecular ratio.		
SiO_2	68.76	1.146	67.6	65.3
Al_2O_3	15.22	.149	16.0	15.1
Fe_2O_3	2.72	.017	2.2	2.6
FeO	1.74	.024	1.6	2.6
MgO	.72	.018	.4	2.1
CaO	1.68	.030	1.2	3.5
Na_2O	4.42	.071	4.4	3.6
K_2O	3.73	.039	5.7	3.7
H_2O+	.66		.7	1.0
H_2O-	.16			
CO_2	None.			
TiO_2	.31	.004	.3	.5
P_2O_5	.15	.001	.1	.2
SO_3	None.			
Cl	Trace.			
MnO	Trace.		.1	.1
BaO	Undet.			
	100.27		100.3	100.3

1. Biotite dacite, Kendrick Peak, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.48.
2. Type trachyte-rhyolite.
3. Type dacite.

Although this lava of Kendrick Peak has typical rhyolitic textures, it is more basic than the rhyolites proper of the region. It resembles both the type trachyte-rhyolite and the type dacite. It can not be easily classified on the basis of chemical composition. Rocks are not aggregates of elements or oxides, but of minerals composed of them. The natural thing is to classify them by their actual mineral composition. This may be expressed to some extent by grouping oxides of similar valence and obtaining ratios between them (the bases) and silica. However, such a method of expressing the mineral composition leads to unsatisfactory results, because it is indirect and does not express the actual facts.

Mineral composition.—The mode might be considered uncertain on account of the glassy character of the lava. The thin sections, however, show the presence of oligoclase, biotite, hornblende, hypersthene, and magnetite; the chemical composition shows that the glass would crystallize into quartz and alkali feldspars. The prevailing mode has biotite as the chief calfemic mineral; a less common mode has hypersthene partly replacing the biotite. These modes are as follows:

Modes of dacite of Kendrick Peak, of type dacite, and of type trachyte-rhyolite.

	1	2	3	4	5	6
Quartz	25.1	24.6	19.5	18.4	+ 5.6	+ 6.7
Orthoclase	19.5	20.6	22.0	30.7	− 2.5	−11.2
Albite	24.7	24.2	19.6	32.5	+ 5.1	− 7.8
Oligoclase (Ab_3An_1)				8.8		
Oligoclase (Ab_5An_3)	20.0	20.8			− 1.2	+11.2
Andesine (Ab_1An_1)			21.2			
Biotite [a]	4.5	2.0		7.0	− 8.3	− 0.2
Hornblende [a]	1.0	1.0	10.0			
Hypersthene [a]		1.3	3.6			
Magnetite	3.2	3.7	3.3	2.0		
Apatite	.3	.3	.4	.2		
Alumina, excess of	.9	.9				
Water	.8	.8	.8	.5		
	100.0	100.2	100.4	100.1	+10.7 −12.0	+17.9 −19.2

[a] Biotite and hornblende from quartz monzonite, Tioga Road, southeast of Mount Hoffman, Cal. (Bull. U. S. Geol. Survey No. 228, 1904, p. 242), used in the modes of the lava of Kendrick Peak. The hypersthene in mode 2 has FeO : MgO : : 1 : 3.

1. Biotite mode of dacite of Kendrick Peak; 2, same with addition of hypersthene; 3, mode of type dacite; 4, mode of type trachyte-rhyolite; 5, departures of mode 1 from mode 3; 6, departures of mode 1 from mode 4.

The relative amounts of biotite, hornblende, and hypersthene in the modes of the lava from Kendrick Peak are estimated from thin sections. After all the minerals have been calculated there remains an excess of nine molecules of alumina, which is left uncombined. As will be shown later, it is probably in the feldspars. The lava is predominantly salic, the quartz, orthoclase, albite, and oligoclase in very nearly equal amounts constituting about 90 per cent of the total. The calculated amount of oligoclase agrees closely with that measured, 18.3 per cent in the type specimen, which indicates that this mineral has probably entirely separated out in phenocrysts. The calculated amount of magnetite, however, is very much greater than the measured amount, the excess consisting partly of groundmass material in quantity too small to be measured.

Comparison of modes shows that the lava of Kendrick Peak more closely resembles the type dacite than the type trachyte-rhyolite, as may be seen by the departures given in columns 5 and 6 of the table. The composition of the plagioclase (Ab_5An_3) is also nearer that of the dacite. The resemblance of the lava chemically to the trachyte-rhyolite thus disappears when mineral composition is considered, owing to the manner in which the oxides have been combined to form the minerals. Quartz and albite are somewhat greater and calfemic minerals noticeably less than in the type dacite. As the chemical analysis shows, the lava is more acidic than the type. It is classified as a biotite dacite.

No. 7. BIOTITE DACITE OF O'LEARY PEAK (LASSENOSE, I.4.2.4).

Occurrence.—Biotite dacite forms the eastern part of O'Leary Peak and the flows just to the north. It also composes a small cone situated 2 miles S. 70° W. of the summit of the mountain.

Megascopic characters.—The lava of the main cone was observed only at the north foot of the mountain, where it is a banded dark-brown and blackish felsite. The lava of the small cone is in part pearl gray in color and has a finely porous to compact aphanitic texture in which flow lines are brought out by thin layers of varying compactness. This variety is nonporphyritic. A black semibrilliant obsidian, which also occurs in the small cone, contains from 5 to 10 per cent of feldspar phenocrysts not over 2 millimeters in length. All varieties have the appearance of typical rhyolites and would be so classified in the field.

Microscopic characters.—The groundmass ranges from holohyaline to holocryptocrystalline. It contains a sprinkling of minute black crystals, some of which may be recognized as biotite and magnetite. The type specimen (2370) is estimated to contain 10 per cent of oligoclase (Ab_5An_3) phenocrysts in slender laths rarely over 0.1 millimeter in length, but in much of the rock these are quite lacking.

Chemical composition.—The analysis of the fresh type specimen (2370) from the north foot of the mountain gave the following results:

Chemical analyses of biotite dacite of O'Leary Peak, type trachyte-rhyolite, and type dacite.

	1		2	3
	Per cent.	Molecular ratio.		
SiO_2	66.98	1.116	67.6	65.3
Al_2O_3	16.47	.161	16.0	15.1
Fe_2O_3	2.31	.014	2.2	2.6
FeO	2.14	.030	1.6	2.6
MgO	.52	.013	.4	2.1
CaO	2.02	.036	1.2	3.5
Na_2O	5.05	.081	4.4	3.6
K_2O	3.32	.035	5.7	3.7
H_2O+	.59	....	.8	1.0
H_2O-	.12	....	....	....
CO_2	None.	....	....	....
TiO_2	.35	.004	.3	.5
P_2O_5	.13	.001	.1	.2
SO_3	None.	....	....	....
Cl	Trace.	....	....	....
MnO	Trace.	....	.1	.1
BaO	Undet.	....	....	....
	100.00	....	100.3	100.3

1. Biotite dacite, O'Leary Peak, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.48.
2. Type trachyte-rhyolite.
3. Type dacite.

The lava of O'Leary Peak is considerably more basic than the rhyolites proper of the region, although it has their typical textures. Like the biotite dacite of Kendrick Peak, which it closely resembles, the chemical composition of the lava appears more like that of the type trachyte-rhyolite than that of the type dacite, except for low potash. On the basis of mineral composition, however, this resemblance is reversed.

Mineral composition.—The mode, calculated from the chemical composition, is as follows:

Modes of dacite of O'Leary Peak, of type dacite, and of type trachyte-rhyolite.

	1	2	3	4	5
Quartz	21.2	19.5	18.4	+ 1.7	+ 2.8
Orthoclase	16.7	22.0	30.7	− 5.3	−12.0
Albite	27.5	19.6	32.5	+ 7.9	− 5.0
Oligoclase (Ab_3An_1)			8.8		
Oligoclase (Ab_5An_3)	23.8			+ 2.6	+15.0
Andesine (Ab_1An_1)		21.2			
Biotite [a]	5.4		7.0		
Hornblende		10.0			
Hypersthene		3.6		− 8.0	− 0.1
Magnetite	3.6	3.3	2.0		
Apatite	.3	.4	.2		
Alumina, excess of	.9				
Water	.5	.8	.5		
	99.9	100.4	100.1	+11.6 −13.3	+17.8 −17.1

[a] Biotite from biotite granite, El Capitan, Yosemite Valley, Cal. (Bull. U. S. Geol. Survey No. 228, 1904, p. 241), used in mode of lava from O'Leary Peak.

1, Biotite mode of dacite of O'Leary Peak; 2, mode of type dacite; 3, mode of type trachyte-rhyolite; 4, departures of mode 1 from mode 2; 5, departures of mode 1 from mode 3.

The lava of O'Leary Peak is predominantly salic; albite and oligoclase are more abundant than quartz and orthoclase. As is shown in the last two columns of the table, the departures in the composition of the O'Leary rock from the type dacite are less than from the type trachyte-rhyolite. Orthoclase and calfemic minerals are lower, but albite is considerably higher. The lava is, on the whole, more salic (or acidic) than the type dacite. This is shown by the slightly more acidic composition of the plagioclase and the presence of biotite rather than hornblende. The lava may be called a biotite dacite.

No. 8. BIOTITE-HORNBLENDE DACITE (LASSENOSE, I.4.2.4).

Occurrence.—Biotite-hornblende dacite occurs in flows at a few localities on San Francisco Mountain, the principal one being east of San Francisco Peak at an elevation of 11,500 feet. It is found as an intrusive in the chimney of the volcano and in dikes.

Megascopic characters.—The rock in general is light to dark gray in color and has a compact aphanitic texture. Idiomorphic phenocrysts of a glassy feldspar, commonly 1 centimeter in length, some of them recognizable as plagioclase, constitute 10 to 20 per cent of the lava. A few quartz crystals are also present. Hornblende in smaller amount occurs as idiomorphic phenocrysts usually not over 1 millimeter but at a maximum 5 millimeters in length.

Microscopic characters.—The groundmass of the lava ranges from hypohyaline to hypomicrocrystalline and generally contains more than 25 per cent of glass. The crystalline part consists predominantly of feldspar laths in parallel arrangement.

Phenocrysts of oligoclase (Ab_5An_3) occur in the form of idiomorphic prismoids whose length is two to three times their width. They are in all sizes from less than 1 millimeter to 1 centimeter in length, but those of 2 millimeters or more predominate. They generally have rounded ends and some of them have corroded interiors.

Biotite and hornblende, invariably more or less resorbed, are the prevailing calfemic minerals, with pyroxene in subordinate amount. The biotite is the common variety showing pleochroism in tones of brown. Sections perpendicular to the vertical axis show numerous round holes containing grains of ore surrounded by a light-colored anisotropic base. The holes are absent in sections showing cleavage, so that the resorbed areas evidently are disk-shaped and not thicker than a few cleavage leaves. The alteration of the outer part of the crystals is considerably greater than that of the interior. The hornblende is of the brown variety in rather long, slender crystals. Some of it is entirely altered to a mass of ore grains embedded in an anisotropic groundmass of low birefringence. Pyroxene is present in much smaller crystals than hornblende or biotite, and in distinction to them is always fresh. The conditions that permitted the formation of the hornblende and biotite were evidently temporary and existed in a preeruptive stage, otherwise these minerals would not be so markedly resorbed. Later conditions were favorable to the formation and preservation of the pyroxene, and in this respect the lava resembles that of the preceding stage of eruption of the volcano.

The only difference between the extrusive and intrusive phases of this rock is in the character of the groundmass. That of the intrusive rock is in all specimens holocrystalline. It ranges from cryptocrystalline in the narrower dikes to microcrystalline in the larger ones and the neck of the volcano. It consists of the same feldspars as occur in the effusive rock, which average under 0.1 millimeter in length, and in addition there are irregular-shaped patches of quartz, the last crystallization product, some of which are poikilitically intergrown with small feldspar crystals.

Crystallinity of the lava.—Three sets of measurements of the type specimen (2111) by the Rosiwal method gave the following results:

Micrometric analyses of biotite-hornblende dacite of San Francisco Mountain.

	1	2	3	Average by volume.	Average by weight.	Average size of crystals (millimeter).
Groundmass	78.6 } 92.3	72.0 } 94.8	72.2 } 93.7	71.7 } 93.8	69.8 } 91.9	....
Feldspar phenocrysts	13.7	22.8	21.5	22.1	22.1	0.09
Hornblende and biotite	4.9	3.9	4.1	4.2	4.9	.26
Pyroxene	1.1 } 7.7	.5 } 5.2	1.0 } 6.3	.8 } 6.2	1.0 } 8.1	.26
Ore	1.7	.9	1.2	1.2	2.2	.02
	100.0	100.0	100.0	100.0	100.0	....

The results are given in full to illustrate the possibilities of the Rosiwal method as applied to porphyritic lavas. The traverses were made as follows:

Directions and distances of traverses in micrometric analysis of biotite-hornblende dacite.

Set.	Individual traverses.	Distance measured (centimeters).
1	Diverse directions	5.3
2	Parallel	6.8
3	Parallel	7.4

The traverses of sets 2 and 3 were made at right angles, on successive days at a time when some experience had been acquired in the use of the method and of the errors that are likely to occur. Set 1 was measured about a year earlier and represents a first trial. The agreement between sets 2 and 3 is very satisfactory and shows that 7 centimeters is a sufficient distance to traverse in a lava where the minerals are exceedingly variable in size and small in amount. The difference in the relative amounts of groundmass and feldspar in set 1, as compared with sets 2 and 3, means that many small feldspars were omitted in the first measurement which were included in the later ones by the exercise of greater care. The sum of groundmass and feldspar, it will be noticed, is throughout in good agreement. In set 1 the dark-colored minerals were somewhat overmeasured. This is a common error but can be eliminated by the exercise of care and practice. The probable correctness of the measured amounts of the minerals will be referred to in the paragraphs on the mineral composition of the lava. The final result is obtained by taking the average of the calfemic minerals for all three sets of traverses, the groundmass and feldspar being based on sets 2 and 3. The groundmass, it will be recalled, represents invariably material less than 0.01 millimeter in size.

Chemical composition.—The following is an analysis of the type specimen (2111) from the locality east of San Francisco Peak. The rock is entirely fresh, except for the partial resorption of the hornblende and biotite.

Chemical analyses of biotite-hornblende dacite of San Francisco Mountain and of type dacite.

	1		2
	Per cent.	Molecular ratio.	
SiO_2	66.50	1.108	65.3
Al_2O_3	16.55	.162	15.1
Fe_2O_3	2.25	.014	2.6
FeO	2.58	.036	2.6
MgO	.87	.022	2.1
CaO	2.75	.049	3.5
Na_2O	4.55	.073	3.6
K_2O	3.36	.036	3.7
H_2O+	.16		1.0
H_2O-	.12		
CO_2	None.		
TiO_2	.59	.007	.5
P_2O_5	.19	.001	.2
SO_3	None.		
Cl	Trace.		
MnO	Trace.		.1
BaO	None.		
	100.47		100.3

1. Biotite-hornblende dacite, San Francisco Mountain, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.56.
2. Type dacite.

The lava of San Francisco Mountain most closely approaches the type dacite in composition. The magnesia is distinctly lower, whereas lime is slightly lower and soda higher, and these features give the lava a trachytic cast. The ratio of potash to soda (1:2) is nearly the same as in the type dacite (1:1.5).

Mineral composition.—The composition can not be calculated directly from the chemical analysis on account of the presence of several calfemic minerals which contain similar oxides. Approximately correct results, however, may be obtained by assuming that the hornblende, biotite, and hypersthene are in the same proportions as determined by measurement. The complete mineral composition is then as follows:

Modes of biotite-hornblende dacite of San Francisco Mountain and of type dacite.

	1	2	3
Quartz	20.0	19.5	+ 0.5
Orthoclase	18.9	22.0	− 3.1
Albite	18.3	19.6	− 1.3
Oligoclase (Ab_5An_3)	30.4		+ 9.2
Andesine (Ab_1An_1)		21.2	
Hornblende [a]	2.5	10.0	
Biotite [a]	2.5		
Hypersthene [a]	1.7	3.6	− 6.6
Magnetite	3.7	3.3	
Apatite	.3	.4	
Alumina, excess of	1.1		
Water	.3	.8	
	99.7	100.4	+ 9.7 −11.0

[a] Biotite and hornblende from quartz monzonite, Tioga road, southeast of Mount Hoffman, Cal., and hypersthene with ratio of FeO : MgO :: 1:1 are used in the mode of the dacite of San Francisco Mountain.

1, Mode of soda dacite of San Francisco Mountain; 2, mode of type dacite; 3, departures of mode 1 from mode 2.

The hypersthene and ore are obtained by the proper adjustment of the magnesia, iron, and titania which remain after the biotite and hornblende have been calculated. The oxides then left go into the salic minerals. There remains an excess of 11 molecules of alumina which can not be used in the formation of any of the known minerals of the lava. The ratio of FeO to MgO (1:1) obtained for the hypersthene is most probably too high and indicates lower magnesia and higher ferrous iron in either the biotite or the hornblende or in both of them.

The lava is predominantly salic in character and the feldspars constitute slightly more than two-thirds of its mass. The calculated amount of oligoclase is 30.4 per cent as compared with 22.1 per cent measured, so that not all of this mineral is in measurable crystals. The composition of the oligoclase was determined in but three individuals, all that were suitable, and a small error would considerably alter the calculated amount. If, for instance, the composition were Ab_4An_3 instead of Ab_5An_3 the difference between the calculated and measured plagioclase would be decreased one-half. From a comparison of the calculated and measured modes it is seen that there is a difference of 3.2 per cent between the total salic components, including the excess of alumina in the calculated mode, and of 2.6 per cent between the dark components. In the calfemic minerals this difference is in part due to the presence of crystals below measurable size in the groundmass, which if taken into account would decrease both differences. The comparison will give an idea of the accuracy of the Rosiwal method as applied to porphyritic lavas containing small amounts of minerals of highly variable size.

As compared with the type dacite, the plagioclase of the dacite of San Francisco Mountain is high and the calfemic minerals are low. The higher plagioclase is due to its more acidic composition. If it were Ab_1An_1, the amount of plagioclase would be less and albite more than in the type. The small amount of the calfemic minerals is in particular the expression of the low magnesia. The lava is classified as a biotite-hornblende dacite.

No. 9. HYPERSTHENE-SODA DACITE (LASSENOSE, I.4.2.4).

Occurrence.—Hypersthene-soda dacite outcrops in the walls of the interior valley and is the predominant lava about the foot slopes and in part the upper slopes of San Francisco Mountain. It occurs as an intrusive in the core and in dikes.

Megascopic characters.—The lava varies in color from light to dark gray, in places reddish, with the darker tones predominant. It is in general compact, although brecciated lower and slaggy upper surfaces are not uncommon, especially about the base of the mountain. It is free from any regular jointing and has a rather massive appearance which is increased by the smooth rounded surfaces not uncommonly produced by erosion. The groundmass is invariably aphanitic and commonly felsitic, although in some places glassy, as at the bottom of the heavy basal flow exposed on the inner slope of San Francisco Peak.

Idiomorphic prismoidal phenocrysts of feldspar, some of them recognizable as plagioclase, constitute 5 to 25 per cent of the lava; in the type specimen (1809) they amount to 16 per cent. They vary greatly in size, ranging from 2 millimeters to 1 centimeter in length, the average being about 3 millimeters. In the type specimen they appear rather more uniform in size than is the rule and average 1 by 3 millimeters in cross section, a few stouter crystals being 5 millimeters square. They are almost invariably arranged with their greatest length parallel to the direction of flow. The prevailing calfemic phenocryst is pyroxene in small idiomorphic crystals, generally recognizable only with the lens. Hornblende occurs very rarely and in small quantity.

The rock which solidified in the chimney of the volcano is very similar to the lava; that in the dikes, however, is uniformly more compact and a very little of it might be considered to have a cryptocrystalline texture.

Microscopic characters.—The groundmass is in general hypohyaline to hypomicrocrystalline, the smallest amount of glassy base being estimated at 25 per cent. The crystals of the groundmass are too small to permit an exact determination of their character, but in the most coarsely crystallized specimens they are mostly alkalic feldspars with a very small amount of pyroxene and possibly magnetite.

Andesine (Ab_1An_1), hypersthene, and small amounts of augite and hornblende occur as phenocrysts. Magnetite, apatite, zircon, and garnet (?) are accessories.

The andesine varies in quantity and especially in size, as already noted. Although a continuous series of crystals could be measured from the largest, 1 centimeter in length, to those of much less than 1 millimeter, most of them are 2 millimeters or more. They are generally prismoids whose length is two to three times their width; a few have stouter forms. They are commonly idiomorphic, many of them have rounded ends, and some of them have corroded interiors. The average composition of the plagioclase is Ab_1An_1, and of the determinable crystals 70 per cent are either Ab_3An_4 or Ab_1An_1. The remainder are in general more acidic.

Zonal structure is not uncommon, the periphery of the crystal being more acidic than the center. The plagioclase is younger than the pyroxene and magnetite, as both are included in it. A small number of albite phenocrysts are also present.

The pyroxenes are hypersthene and augite, the former greatly predominant. The hypersthene occurs in automorphic crystals, many of them having rounded ends. Interior corrosion is also common, the cavities being filled with the groundmass of the lava. The common forms are elongated prisms ranging from a maximum length of 2 millimeters to a few hundredths of a millimeter. There is an evident pleochroism in the hypersthene, where x=light brown, y=yellow, and z=light green. The acute bisectrix generally emerges from the prismatic zone and in one crystal the bars of the interference figure just touch the edges of the field of a No. 7 objective, indicating a small axial angle. The interference figure is always negative. These features show that the hypersthene is rich in ferrous iron. Apatite, zircon, and magnetite occur as inclusions, and there is commonly an intimate association between the magnetite and pyroxene. Parallel intergrowths of hypersthene in augite, or the reverse, are common.

Hornblende is rare; it was seen in but 2 out of over 30 thin sections. It replaces the pyroxene and is either very much or completely altered. Magnetite occurs in crystals which range from 0.02 to 4 millimeters in diameter, the average being 0.08 millimeter. They are commonly slightly altered about the edges to limonite. Apatite and zircon are present in negligible quantities, as is also the garnet.

The intrusive phase of the rock in the neck of the volcano and in dikes carries phenocrysts of the same character as the lava. The groundmass, however, is invariably holocrystalline. In the narrower dikes it may be considered as cryptocrystalline, but in the larger ones and the neck it becomes microcrystalline. It is composed of the same feldspars as the lava in larger crystals, which, however, average less than 0.1 millimeter in length. In addition, there are irregular-shaped patches of quartz, the last crystallization product, many of them poikilitically intergrown with the small feldspars. Evidently, then, the quartz in the effusive rock, as it can not be seen, has remained uncrystallized and must constitute a very considerable portion of the glassy base. This fact is of some interest, because the absence of quartz would presumably cause the lava to be classified as an andesite. In fact, an analyzed rock of identical composition from this region has been called a "typical" hypersthene andesite.[1] It is only when the complete mineral composition has been calculated, and a strictly quantitative idea thus obtained, that the true nature of the lava is clearly seen. For this reason the mineral composition of all the lavas considered in this report has been calculated on a holocrystalline basis, even though for some lavas the result may not be exactly correct. Where the minerals in a lava are simple and mutually exclusive in composition, or, if not, where their quantities may be determined by measurement, the actual mineral composition may be calculated with reasonable success. This is, however, frequently a tedious process, and if approximate results are desired, it is simpler to calculate the norm according to the rules given in the quantitative system of classification.[2]

Crystallinity of the lava.—An idea of the average extent to which the lava has crystallized may be obtained from the micrometric analyses of the type specimen (1809).

Micrometric analyses of hypersthene-soda dacite of San Francisco Mountain.

	A	B	Average by volume.	Average by weight.	Average size of crystals (millimeter).
Groundmass	76.6 } 94.4	78.6 } 93.7	77.6	74.6 } 91.3	....
Plagioclase (Ab_1An_1)	17.8	15.1	16.4	16.7	0.38
Pyroxene	3.8 } 5.6	4.8 } 6.3	4.3	5.6 } 8.7	.26
Ore	1.3	1.2	1.3	2.5	.08
Garnet	.5	.3	.4	.6	....
	100.0	100.0	100.0	100.0	....

[1] Bull. U. S. Geol. Survey No. 228, 1904, p. 202.

[2] Cross, W., Iddings, J. P., Pirsson, L. V., and Washington, H. S., Quantitative classification of igneous rocks, University of Chicago Press, 1903.

The two sets of traverses were made at right angles. The distance traversed in set 1 was 11.7 centimeters, and in set 2, 13.0 centimeters, which appears sufficient to give reasonably satisfactory results. The differences in the quantities of groundmass and feldspar are due to the failure to measure small crystals of the feldspar in the second set; the sums of groundmass and feldspar are in good agreement. An inspection of the thin sections indicates that the calfemic minerals have largely separated out in measurable crystals, so that 8.7 per cent is nearly their correct amount.

Chemical composition.—The analysis of the type specimen (1809), from the lower part of the basal flow exposed on the inner slope of San Francisco Peak, gave the following results:

Chemical analyses of hypersthene-soda dacite of San Francisco Mountain and of type dacite.

	1		2
	Per cent.	Molecular ratio.	
SiO_2	64.60	1.077	65.3
Al_2O_3	16.60	.163	15.1
Fe_2O_3	{ 2.62 [a]2.3	.016	2.6
FeO	{ 2.38 [a]2.66	.033	2.6
MgO	.93	.023	2.1
CaO	3.06	.055	3.5
Na_2O	5.12	.083	3.6
K_2O	3.43	.036	3.7
H_2O+	.10	....	1.0
H_2O-	.18	....	....
CO_2	None.	....	....
TiO_2	.80	.010	.5
ZrO_2	Undet.	....	....
P_2O_5	.18	.001	.2
SO_3	None.	....	....
Cl	Trace.	....	....
MnO	.06	.001	.1
SrO	None.	....	....
BaO	.04	....	....
	100.10	....	100.3

[a] Corrected value for fresh rock.

1. Hypersthene-soda dacite, San Francisco Mountain, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.66.
2. Type dacite.

The lava of San Francisco Mountain is very similar in composition to the type dacite, except for lower magnesia and higher soda. The ratio of potash to soda (1:2.3) is noticeably greater than in the type dacite and marks the lava as a soda dacite. Although silica is the same in both rocks, it is evident that the lava of San Francisco Mountain contains less quartz, as the molecular sum of the lime and alkalies exceeds that of the type dacite.

Mineral composition.—The common mode has hypersthene as the chief calfemic mineral. Values of 2.3 per cent for ferric and 2.66 per cent for ferrous iron have been substituted for those obtained by analysis in order to allow for the slight alteration of the magnetite, and a small amount of iron-garnet has been introduced. The result is as follows:

Modes of soda dacite of San Francisco Mountain and of type dacite.

	1	2	3
Quartz	13.7	19.5	− 5.8
Orthoclase	20.0	22.0	− 2.0
Albite	31.3	19.6	+11.7
Andesine (Ab_1An_1)	24.4	21.2	+ 3.2
Hornblende	....	10.0	} − 7.2
Hypersthene	3.7	3.6	
Augite	1.1	....	
Magnetite	4.5	3.3	
Apatite	.3	.4	
Garnet	.5	....	
Water	.3	.8	....
	99.8	100.4	{ +14.9 −15.0

1 Mode of soda dacite of San Francisco Mountain; 2, mode of type dacite; 3, departures of mode 1 from mode 2.

The lava is predominantly salic, the feldspars alone forming three-quarters of the total. Albite is higher and quartz and calfemic minerals somewhat lower than in the type. The high soda is expressed in the albite, as the plagioclase has the same composition and is present in about the same amount as in the type. The lava is classified as a hypersthene-soda dacite. The prefix soda indicates that soda predominates over potash to a greater extent than in the type dacite, which contains the alkalies in nearly equal amounts.

No. 10. HYPERSTHENE-HORNBLENDE-SODA DACITE (LASSENOSE, I.4.2.4).

Occurrence.—Hypersthene-hornblende-soda dacite forms nearly the entire mass of Elden Mountain.

Megascopic characters.—The rock is commonly light to dark gray, in places yellowish. It is in general compact, although a few drusy cavities are present, and it has a massive appearance. The groundmass is aphanitic and contains phenocrysts of feldspar and dark minerals. Some of the feldspar is recognized as plagioclase, but the amount can not easily be estimated, as the crystals tend to blend in color with the rock. The calfemic minerals are estimated to form 5 to 10 per cent of the rock. They are in small crystals, generally less than 1 millimeter in length, which are all more or less altered. Very commonly the groundmass is sprinkled with minute black crystals of undeterminable character.

Microscopic characters.—The groundmass ranges from cryptocrystalline to microcrystalline, and generally contains a small proportion of glass. It consists predominantly of feldspar in automorphic prismoidal or tabular crystals and possibly of quartz. The small size of the crystals makes it difficult to determine their exact character. Flow structure is not well marked; it is commonly indistinctly visible but in some specimens is entirely lacking.

The plagioclase phenocrysts occur in rather shattered subhedral prisms up to 3 millimeters in length. They are fresh and have an average composition of Ab_1An_1. The calfemic minerals are hypersthene, augite, and hornblende. The pyroxenes are commonly more or less altered and the hornblende is as a rule entirely changed to dull brown or black opaque masses which preserve the outlines of the original crystals. Hypersthene is the characteristic dark mineral but is partly replaced by hornblende; only a subordinate quantity of augite is present. Magnetite occurs in fresh crystals averaging 0.03 millimeter in diameter, as also does apatite in very small quantity.

Crystallinity of the lava.—The micrometric analysis of two slides gave the following results:

Micrometric analyses of hypersthene-hornblende-soda dacite of Elden Mountain.

	1		2		Average size of crystals (millimeters).	
					1	2
Groundmass	72.8	91.3	72.0	91.5		
Plagioclase (Ab_1An_1)	18.5		19.5		0.70	0.86
Calfemic minerals	8.7		8.5		.12	.14
	100.0		100.0			

1. Type specimen 2364, Elden Mountain.
2. Specimen 2209, south slope.

The analyses bear out the impression derived from hand specimens and thin sections that the rock is decidedly uniform in character. The dark minerals are grouped together, as their altered state makes it difficult to discriminate between them. They appear to have entirely separated out, so that the measured amount is correct, except for a small proportion in the groundmass. The lava has essentially the same degree of crystallinity as the corresponding lavas that occur elsewhere in the region.

Chemical composition.—The analysis of the type specimen (2364), which is entirely fresh except for the dark minerals, is given on the next page.

Chemical analyses of hypersthene-hornblende-soda dacite of Elden Mountain and related rocks.

	1		2	3
	Per cent.	Molecular ratio.		
SiO_2	65.92	1.099	65.3	64.85
Al_2O_3	17.12	.168	15.1	18.27
Fe_2O_3	4.68 (2.55)	.016	2.6	3.48
FeO	.15 (2.15)	.030	2.6	.56
MgO	.86	.021	2.1	.85
CaO	2.59	.046	3.5	2.89
Na_2O	4.49	.073	3.6	5.05
K_2O	3.10	.033	3.7	2.67
H_2O+	.26		1.0	.20
H_2O-	.10			
CO_2	None.			
TiO_2	.51	.006	.5	.56
P_2O_5	.25	.002	.2	.23
SO_3	None.			
Cl	Trace.			
MnO	Undet.		.1	.10
BaO	Undet.			
	100.05		100.3	99.78

1. Hypersthene-hornblende-soda dacite, Elden Mountain, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.60.
2. Type dacite.
3. Typical hypersthene andesite, San Francisco Mountains, Arizona. T. M. Chatard, analyst. (Bull. U. S. Geol. Survey No. 228, 1904, p. 202.)

The lava of Elden Mountain approaches the type dacite most closely in chemical composition. It has, however, noticeably lower magnesia as well as lower lime and higher soda. The ratio of potash to soda is 1:2.2, as compared with 1:1.5 in the type dacite. Owing to the alteration of the dark minerals, the iron is almost wholly in the ferric state. Corrected amounts obtained from the calculated mineral composition, and more nearly representing the true values for the fresh rock, are given in parentheses. The lava is almost the exact counterpart of the dacites of San Francisco Mountain, and, like them, is classified as a soda dacite.

The specimen whose analysis is given in column 3 is only known to have come from the San Francisco Mountains. A comparison with the analyses of similar rocks of the region shows that in all probability it was collected at Elden Mountain. This conclusion is based on the high ferric and low ferrous iron and the accessibility of the locality to collectors.

Mineral composition.—The mode of the lava is as follows:

Modes of soda dacite of Elden Mountain and of type dacite.

	1	2	3
Quartz	21.2	19.5	+ 1.7
Orthoclase	18.4	22.0	− 3.6
Albite	28.3	19.6	+ 8.7
Andesine (Ab_1An_1)	20.0	21.2	− 1.2
Hypersthene[a]	2.4	3.6	− 8.0 (Hypersthene, Hornblende, Magnetite, Apatite)
Hornblende[a]	2.0	10.0	
Magnetite	4.2	3.3	
Apatite	.7	.4	
Alumina, excess of	2.5		
Water	.4	.8	
	100.1	100.4	+10.4 −12.8

[a] Hornblende from quartz monzonite, Tioga road, southeast of Mount Hoffman, Cal., and hypersthene with ratio of FeO : MgO : : 1 : 2 used in mode of lava of Elden Mountain.

1, Mode of soda dacite of Elden Mountain; 2, mode of type dacite; 3, departures of mode 1 from mode 2.

The amount of hornblende and hypersthene is governed by magnesia, their relative proportions being estimated from thin sections. The rest of the ferric iron and titania and an equal amount of ferrous iron form magnetite and ilmenite. The readjusted values of ferric and ferrous iron for the fresh rock thus obtained are: Fe_2O_3, 2.55; FeO, 2.15. The feldspars are calculated according to their theoretical composition. Besides the excess of quartz, there remains 2.5 per cent of alumina over that needed in the formation of the known minerals.

The lava is decidedly salic, and the feldspars form two-thirds of the total. As compared with the type dacite, albite is high and calfemic minerals low, relations which express the soda-rich and magnesia-poor character of the lava. It is classified as a hypersthene-hornblende-soda dacite.

No. 11. HORNBLENDE-SODA DACITE OF MORMON MOUNTAIN (LASSENOSE, I.4.2.4).

Occurrence.—The hornblende-soda dacite here described was observed only as a partly detached knob whose summit has an elevation of 8,250 feet on the southwest side of Mormon Mountain.

Megascopic characters.—The lava is generally banded light gray and pale pink in color, and has a finely rough feel. The groundmass is aphanitic, and contains about 20 per cent of automorphic feldspar phenocrysts and 10 per cent of hornblende. The feldspar is in tabular or stout prismatic crystals, which generally do not exceed 2 millimeters in length, though a few individuals reach a maximum of 5 millimeters. Some of the larger phenocrysts have a central portion, of automorphic outline, stained bright red, which in turn is surrounded by a border of colorless feldspar, thus clearly indicating two stages of crystallization. The hornblende is black and occurs in slender idiomorphic prisms, few of which are over 5 millimeters in length. They have a parallel arrangement that conforms to the banding of the lava and emphasizes the flow structure.

Microscopic characters.—From 50 to 75 per cent of the groundmass is glassy to cryptocrystalline. The remainder consists of diversely arranged microscopic tabular feldspars and a colorless mineral with a higher index of refraction and parallel extinction, presumably an orthorhombic pyroxene.

The feldspar phenocrysts belong to two generations. The earlier crystals are by far the largest in size, and besides being stained red, as observed megascopically, are internally corroded. They are plagioclase, whose composition could not be determined for lack of proper sections. The crystals of the second generation are much smaller in size, the average diameter, as measured on Rosiwal traverses, being 0.04 millimeter. They occur predominantly as fresh stout tabular crystals of a composition between Ab_1An_1 and Ab_3An_4.

The hornblende is in rather slender automorphic crystals, commonly lacking terminal faces. The largest crystal in the type slide (2384) measures 1.5 millimeters, but the average diameter of all, as measured on straight traverses, is 0.06 millimeter. The axes of elasticity have the usual position, and the angle of extinction varies between 10° and 20°. The pleochroism is well marked—x = light green or yellowish green, y and z = deep red-brown. The crystals are somewhat altered, as is brought out by the values of ferric and ferrous iron determined by analysis. They are free from inclusions.

A small quantity of magnetite is present, the average diameter of the crystals being 0.02 millimeter. Insignificant quantities of apatite and garnet(?) also occur.

Crystallinity of the lava.—The micrometric analysis of the type slide (2384) gave the following results:

Micrometric analysis of hornblende-soda dacite of Mormon Mountain.

	Composition by weight.		Average size of crystals (millimeter).
Groundmass	71.3	89.9	
Feldspar	18.6		0.07
Hornblende	8.1	10.0	.06
Ore	1.9		.02
	100.0		

The groundmass is the dominant physical feature of the lava, as the measurable crystals constitute less than 30 per cent of the whole. The actual amount of the calfemic minerals is slightly larger than that measured, because there are individuals in the groundmass, but the difference would not change the highly salic character of the lava as above shown.

Chemical composition.—The analysis of the type specimen (2384) gave the following results:

Chemical analyses of hornblende-soda dacite of Mormon Mountain and of type dacite.

	1		2
	Per cent.	Molecular ratio.	
SiO_2	66.85	1.114	65.3
Al_2O_3	16.48	.162	15.1
Fe_2O_3	2.96 (1.4)	.... .009	2.6
FeO	.43 (1.8)	.... .025	2.6
MgO	1.27	.032	2.1
CaO	3.06	.055	3.5
Na_2O	4.70	.076	3.6
K_2O	2.48	.026	3.7
H_2O+	1.66	....	1.0
H_2O-	.09	....	....
CO_2	None.	....	....
TiO_2	.39	.005	.5
P_2O_5	.11	.001	.2
SO_3	None.	....	....
Cl	Trace.	....	....
MnO	Undet.	....	.1
BaO	Undet.	....	....
	100.48	....	100.3

1. Hornblende-soda dacite, Mormon Mountain, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.48.
2. Type dacite.

The lava of Mormon Mountain approaches rather closely to the type dacite in chemical composition but has the regional characteristic of an excess of soda over potash, the ratio of the latter to the former being 1:2.9, as compared with 1:1.5 in the type dacite. Corrected values for ferric and ferrous iron which more nearly represent the amounts that would occur in the fresh rock are given in parentheses. They have been obtained in calculating the mode of the lava.

Mineral composition.—The complete mineral composition, with the amount of hornblende taken from the micrometric analysis, is as follows:

Modes of soda dacite of Mormon Mountain and of type dacite.

	1	2	3
Quartz	22.0	19.5	+ 2.5
Orthoclase	14.5	22.0	− 7.5
Albite	31.5	19.6	+11.9
Andesine (Ab_4An_5)	17.5	....	− 3.7
Andesine (Ab_1An_1)	....	21.2	....
Hornblende [a]	8.0	10.0	− 6.2
Hypersthene	.9	3.6	
Magnetite	1.9	3.3	
Apatite	.3	.4	
Alumina, excess of	2.0	....	....
Water	1.6	.8	....
	100.2	100.4	+14.5 −17.4

[a] Hornblende from quartz monzonite, Tioga road, southeast of Mount Hoffman, Cal., used in mode of the lava of Mormon Mountain.
1, Mode of soda dacite of Mormon Mountain; 2, mode of type dacite; 3, departures of mode 1 from mode 2.

The lava is decidedly salic, the feldspars alone forming two-thirds of the mode. As compared with the type dacite, orthoclase and calfemic minerals are somewhat low, whereas albite is high. The lava is classified as a hornblende-soda dacite.

No. 12. HORNBLENDE-SODA DACITE OF BILL WILLIAMS MOUNTAIN (LASSENOSE, I.4.2.4).

Occurrence.—The hornblende-soda dacite described below forms the outer part of Bill Williams Mountain and the cones to the northeast. It also occurs as a waterlaid ash, containing numerous fragments of pumiceous lava, which fills the valley through which the logging railroad runs, about 2 miles south of Williams.

Megascopic characters.—The lava is rather uniformly compact and ranges from light to dark gray in color. The groundmass is aphanitic and contains prismoidal phenocrysts of feldspar and hornblende with very small amounts of biotite and quartz. The feldspar, some of which is recognizable as plagioclase, occurs in variable amounts between 5 and 25 per cent. The crystals also vary in size; in the distinctly vitreous flows they average about 1 millimeter in length, but in the more felsitic lavas they are commonly from 3 to 5 millimeters, with a maximum of 1 centimeter. The predominant dark mineral is hornblende in slender black crystals few of which are over 1 millimeter in length, the maximum being 4 millimeters. It is estimated to form 5 to 10 per cent of the lava.

The intrusive core rocks are indistinguishable from the lavas in hand specimens but may be recognized in mass by their different topographic expression and in places by their vertical flow structure.

Microscopic characters.—The groundmass of both the lava and the rock of the cores is generally cryptocrystalline, but is also hyaline or microcrystalline. It is estimated that even in the most coarsely crystallized specimens one-half the groundmass is cryptocrystalline. The predominant mineral is feldspar in automorphic laths, which average, at a maximum, possibly 0.05 millimeter in length. A very small quantity of pyroxene (?) and magnetite in minute crystals also occurs.

Andesine (Ab_1An_1), hornblende, and biotite, in automorphic crystals, are present as phenocrysts. They represent two stages of crystallization. During the first all three minerals separated out; in the second only plagioclase and hornblende crystallized. The distinction is based on the larger size of the crystals of the first stage and the fact that they are more or less resorbed, whereas those of the second stage are unaltered.

The andesine has an average composition of Ab_1An_1. The largest individuals are seen megascopically; the average size of the smaller ones, as measured on straight traverses, is 0.1 millimeter. Resorption has produced many cavities in the larger crystals, which are filled with groundmass.

The hornblende occurs in crystals of two sizes, as does the plagioclase, the average diameter of the smaller ones being 0.06 millimeter. The larger crystals are commonly somewhat resorbed and perforated with holes which contain one or more magnetite grains embedded in a colorless anisotropic base of rather low birefringence. The smaller hornblende crystals are as a rule perfectly fresh, although some of them are externally very slightly resorbed. The y axis of elasticity coincides with crystallographic b, and z lies next to $\dot{c}$, the extinction angle being $+12°$. The pleochroism is marked, but not strong, where x = light brown, y = pale yellow, and z = light green. The biotite is of the ordinary brown variety and is resorbed in the same way as the hornblende. The average diameter of the crystals is 0.5 millimeter.

Magnetite, apatite, and zircon, the last two in very small quantities, occur as accessories. The greater part of the magnetite is in measurable crystals whose average diameter is 0.03 millimeter, the maximum being 0.15 millimeter. Magnetite and apatite are in some specimens inclosed in the hornblende, whereas magnetite and zircon are found in the biotite.

Crystallinity of rock.—An idea of the crystallinity of the rock may be obtained from the micrometric analysis of the type specimen (2351) from the main core of the volcano.

Micrometric analysis of hornblende-soda dacite of Bill Williams Mountain.

	Percentage by weight.		Average size of crystals (millimeter).
Groundmass	77.2	88.8	....
Plagioclase (Ab_1An_1)	11.6		0.10
Hornblende	6.2	11.2	0.06
Biotite	1.9		0.50
Ore	3.1		0.03
	100.0		....

Over three-quarters of the rock consists of a cryptocrystalline groundmass. The specimen was collected from the core at a horizon estimated to be 1,500 feet below the original summit of the cone, as shown by the cross sections (fig. 12, p. 60). The fine grain of the rock would seem to indicate, however, that the distance at which it solidified below the surface was somewhat less. If the crater had a depth equal to the diameter of the vent, this distance would be about 500 feet.

Chemical composition.—The analysis of the type specimen (2351), which is entirely fresh, gave the following results:

Chemical analyses of hornblende-soda dacite of Bill Williams Mountain and of type dacite.

	1		2
	Per cent.	Molecular ratio.	
SiO_2	65.99	1.100	65.3
Al_2O_3	16.14	.158	15.1
Fe_2O_3	2.28	.014	2.6
FeO	1.84	.025	2.6
MgO	1.47	.037	2.1
CaO	3.57	.064	3.5
Na_2O	4.73	.076	3.6
K_2O	2.90	.031	3.7
H_2O+	.67		1.0
H_2O-	.15		
CO_2	None.		
TiO_2	.68	.008	.5
ZrO_2	Present.		
P_2O_5	.15	.001	.2
SO_3	None.		
Cl	Trace.		
MnO	Undet.		.1
BaO	Undet.		
	100.57		100.3

1. Hornblende-soda dacite, Bill Williams Mountain, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.53.
2. Type dacite.

The lava of Bill Williams Mountain is very similar to the type dacite. The principal difference is the lower potash and the San Franciscan cast of a higher ratio of potash to soda (1:2.4) than the type dacite. It is classified as a soda dacite.

Mineral composition.—The dacite of Bill Williams Mountain has nearly the same composition as the granites of the Yosemite National Park, California,[1] so that the analyses of hornblende and biotite from the quartz monzonite of that region may be used in calculating its mineral composition. The relative amounts of the two minerals are taken from the micrometric analysis. The detailed process of calculation is as follows:

Calculation of mineral composition of hornblende-soda dacite of Bill Williams Mountain.

	Percentage.	SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	MgO.	CaO.	Na_2O.	K_2O.	H_2O+.	H_2O-.	TiO_2.	P_2O_5.	MnO.	Cl.
Percentage		65.99	16.14	2.28	1.84	1.47	3.57	4.73	2.90	0.67	0.15	0.67	0.15		
Apatite	0.37						.20						.15		0.02
Magnetite	2.5			1.70	.78										
Ilmenite	.6				.29							.32			
Hornblende	6.2	2.80	.44	.30	.66	.81	.74	.05	.03	.11		.22		0.03	
Biotite	1.9	.68	.28	.09	.27	.23			.18	.07		.06			
Sum		3.48	.72	2.09	2.00	1.04	.93	.05	.21	.18		.60	.15	.03	.02
Remainder		62.51	15.44	.19	− .16	.43	2.64	4.68	2.69	.49	.15	.08			
Molecular ratios		1.042	.151			.009	.047	.075	.029						
Orthoclase	16.2	.174	.029						.029						
Albite	39.4	.450	.075					.075							
Anorthite	13.1	.094	.047				.047								
Enstatite	.9	.009				.009									
Quartz	18.7	.311													

[1] Bull. U. S. Geol. Survey No. 228, 1904, pp. 240–242.

The calculation is given in full to illustrate the process used in obtaining the mineral composition of the rocks in general and the degree of success that may result under favorable conditions. The apatite, hornblende, and biotite are first calculated out, then magnetite and a small amount of ilmenite to equal the measured quantity of 3.1 per cent. The salic components are then figured on the basis of their theoretical composition. There remain small excesses of ferric iron, magnesia, titania, and water and a small deficiency of ferrous iron. It seems permissible to put the ferric iron in the feldspars, as the analyses of those minerals in Dana's Mineralogy show that they almost invariably contain it in small amount. The deficiency in ferrous iron may be eliminated and the excess in magnesia partly reduced by assuming that the hornblende in the rock of Bill Williams Mountain differs slightly with respect to those two oxides from the hornblende of the Yosemite Park rock. The remaining magnesia is put into enstatite to form the pyroxene which is in the groundmass of the lava. The excess of titania is unaccounted for and with the water is left uncombined. The analysis of the lava was not made in duplicate, so that errors from this source have to be left out of consideration. They would not be of sufficient magnitude, in any event, to greatly change the results.

The mode of the lava is as follows:

Modes of soda dacite of Bill Williams Mountain and of type dacite.

	1	2	3
Quartz	18.7	19.5	− 0.8
Orthoclase	16.2	22.0	− 5.8
Albite	26.3	19.6	+ 6.7
Andesine (Ab_1An_1)	26.2	21.2	+ 5.0
Hornblende	6.2	10.0	} − 4.8
Hypersthene	....	3.6	
Biotite	1.9	....	
Enstatite	.9	....	
Magnetite	3.1	3.3	
Apatite	.4	.4	
Water	.6	.8	....
	100.5	100.4	} +11.7 −11.2

1, Mode of soda dacite of Bill Williams Mountain; 2, mode of type dacite; 3, departures of mode 1 from mode 2.

The lava is predominantly salic and the feldspars form over two-thirds of the mode. The departures from the type dacite are not great. The rock is classified as a hornblende-soda dacite.

No. 13. PYROXENE DACITE (TONALOSE, II.4.3.4).

Occurrence.—Pyroxene dacite is found at Kendrick Peak, where it is the surface rock on the northwest slope. It also outcrops on the northeast and southeast arms of the mountain, where it immediately overlies the biotite dacite.

Megascopic characters.—The lava varies in color from light to dark gray, in places taking on a brownish tone. It is usually compact, but some of it is slightly porous and has a finely rough feel; a thin-banded flow structure results from the alternation of the two textures. The groundmass is aphanitic and contains 10 to 20 per cent of idiomorphic phenocrysts of feldspar, whose average length is between 2 and 3 millimeters, the maximum being 5 millimeters. A small amount of pyroxene also occurs as phenocrysts.

Microscopic characters.—The groundmass of the lava ranges from hypohyaline to hypomicrocrystalline, and the glassy matrix forms from one-third to one-half of the total. The only recognizable minerals are feldspar, orthorhombic pyroxene, and magnetite. The feldspar is in idiomorphic laths which generally have an approximate parallel arrangement. A noticeable number of minute prismoids of pyroxene are present, but their exact composition, as well as that of the feldspar, can not well be determined. Magnetite is less abundant.

Plagioclase of the average composition Ab_5An_4, augite, hypersthene, and sporadic hornblende occur as phenocrysts. Magnetite and apatite are present as accessories.

The plagioclase is in idiomorphic prisms, whose length is about twice their diameter. The crystals are larger and more sharply marked off from the groundmass in the lava on the northeast and southeast arms of the cone than in that on the northwest slope. At the latter locality they occur in all sizes from a maximum length of 1.5 millimeters to a fraction of a millimeter (specimen 2154), presumably representing a single stage of growth. Zonal structure is not uncommon, with the periphery of the crystal more acidic than the center. The prevailing composition is Ab_5An_3, but there are subordinate amounts of Ab_1An_1 and Ab_3An_4. The average is placed at Ab_5An_4.

The characteristic calfemic phenocryst is augite, with hypersthene in minor amount. It occurs in idiomorphic crystals, ranging in size from 0.5 millimeter to fractions of a millimeter. Some of the crystals inclose grains of magnetite and are inclosed in the feldspar. A faint pleochroism is seen in some of the hypersthene, but generally it is lacking in both this mineral and the augite. The pyroxene is perfectly fresh in the lava on the northwest slope, but in that on the northeast and southeast arms of the cone it is entirely altered to a dark-brown opaque mass, accompanied by a staining of the groundmass. The alteration was caused by the heat of the extensive flows of the lava of the succeeding stage of eruption.

Crystallinity of lava.—The micrometric analysis of specimen No. 2153, from the northwest slope of the mountain, gave the following results:

Micrometric analyses of pyroxene dacite of Kendrick Peak.

	Composition by weight.		Average size of crystals (millimeter).
Groundmass	71.5	90.0	....
Plagioclase (Ab_5An_4)	18.5		0.14
Pyroxene	7.0	10.0	.07
Ore	3.0		.03
	100.0		....

The analysis may be taken to represent fairly the crystallinity of the lava, as illustrated by thin sections of a number of specimens. The groundmass is the dominant feature. Measurable crystals constitute less than one-third of the lava and the proportion that may be considered as phenocrysts is still smaller. The measured 10 per cent of calfemic minerals is somewhat less than the total because of the presence of groundmass individuals.

Chemical composition.—The analysis of the type specimen (2154) from the northwest slope of the mountain gave the following results:

Chemical analyses of pyroxene dacite of Kendrick Peak, of type dacite, and of type latite.

	1		2	3
	Per cent.	Molecular ratio.		
SiO_2	61.96	1.032	65.3	59.4
Al_2O_3	17.04	.167	15.1	17.6
Fe_2O_3	2.71	.017	2.6	3.3
FeO	2.66	.037	2.6	3.1
MgO	2.41	.060	2.1	2.2
CaO	3.99	.071	3.5	4.2
Na_2O	4.00	.065	3.6	4.3
K_2O	3.10	.033	3.7	4.3
H_2O+	.89	....	1.0	1.0
H_2O-	.21	....	....	....
CO_2	None.	....	....	....
TiO_2	.87	.011	.5	.5
P_2O_5	.22	.002	.2	.2
SO_3	None.	....	....	....
Cl	Trace.	....	....	....
MnO	Trace.	....	.1	.1
BaO	Undet.	....	....	....
	100.06	....	100.3	100.2

1. Pyroxene dacite, Kendrick Peak, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.59.
2. Type dacite.
3. Type latite.

Some of the more basic dacites of the region resemble the type latite. The difference between the type dacite and the type latite is not great; the latter has somewhat lower silica and higher alkalies, iron, and lime. On the basis of the chemical analysis, therefore, it may be difficult to say which type a rock most resembles.

Mineral composition.—The mode of the lava is as follows:

Modes of dacite of Kendrick Peak, type dacite and type latite.

	1	2	3	4	5
Quartz	16.0	19.5	6.4	− 3.5	+ 9.6
Orthoclase	18.4	22.0	25.1	− 3.6	− 6.7
Albite	18.0	19.6	25.7	− 1.6	− 7.7
Andesine (Ab_5An_4)	28.0	....	....	+ 6.8	+ 5.0
Andesine (Ab_1An_1)	....	21.2	....	....	....
Andesine (Ab_4An_5)	....	....	23.0	....	....
Augite	5.0	....	....		
Orthorhombic pyroxene	5.3	....	....		
Hornblende	....	10.0	12.0	− 1.3	− 2.9
Hypersthene	....	3.6	2.1		
Magnetite	5.2	3.3	4.4		
Apatite	.5	.4	.4		
Alumina, excess of	2.0	....	....	....	....
Water	1.1	.8	.8	....	....
	100.1	100.4	99.9	+ 6.8 −10.0	+14.6 −17.3

1, Mode of dacite of Kendrick Peak; 2, mode of type dacite; 3, mode of type latite; 4, departures of mode 1 from mode 2; 5, departures of mode 1 from mode 3.

The character of the pyroxene could not be determined in thin section. It is considered augite in order to reduce the excess of alumina and the amount is placed at 5 per cent. In the absence of an analyzed mineral from a similar rock, an augite of average composition is used.[1] The ferric iron and titania remaining after the calculation of the augite, with an equal proportion of ferrous iron, form magnetite and ilmenite. The ferrous iron and magnesia left over, with equal silica, form orthorhombic pyroxene. The composition of this mineral is: SiO_2, 57.5; FeO, 9.4; MgO, 33.1; total, 100. It thus consists of both hypersthene and enstatite.

The lava is decidedly salic and the feldspars form slightly over two-thirds of the total. As may be seen from the departures given in columns 4 and 5 of the table, the rock more closely resembles the type dacite than type latite. The only noticeable difference from the former type is in the greater amount of andesine, which is due partly to its more acidic composition. The lava is classified as a pyroxene dacite.

No. 14. HYPERSTHENE DACITE (TONALOSE, II.4.3.4).

Occurrence.—Hypersthene dacite is the surface rock of the uneroded parts of the eastern slopes of Kendrick Peak, except about the base, where it is covered by the basalt.

Megascopic characters.—The lava is uniformly dark gray in color and has a compact to finely porous texture. The groundmass is aphanitic and contains from 15 to 25 per cent of feldspar phenocrysts. They are commonly rather slender prismoids, averaging about 2 millimeters in length, with a few stouter crystals of larger size, and have an approximately parallel arrangement. A few phenocrysts of pyroxene are also present.

Microscopic characters.—The lava is very similar in appearance to the pyroxene dacite (2154) which was erupted in the preceding stage of activity of Kendrick Peak. It is marked, however, by a greater proportion of calfemic minerals in the groundmass. The plagioclase phenocrysts are more basic (Ab_3An_4) and are more abundant. Orthorhombic pyroxene, which in the phenocrysts is hypersthene, is relatively more abundant than augite as compared with the pyroxene dacite (2154). Hornblende is entirely lacking.

Crystallinity of lava.—The micrometric analysis of the type specimen (1874), from the northeast arm of the mountain, gave the following results:

[1] Iddings, J. P., Rock minerals, 1906, pp. 298–299, analyses 11–46. Composition: SiO_2, 47.5; Al_2O_3, 6; Fe_2O_3, 3; FeO, 6.5; MgO, 13; CaO, 21.5; Na_2O, 0.8; K_2O, 0.3; H_2O, 0.5; TiO_2, 1; MnO, 0.2; total, 100.

Micrometric analysis of hypersthene dacite of Kendrick Peak.

	Composition by weight.		Average size of crystals (millimeters).
Groundmass	66.5	88.5	....
Plagioclase (Ab_3An_4)	22.0		0.22
Pyroxene	9.5	11.5	.14
Ore	2.0		.03
	100.0		....

The groundmass constitutes two-thirds of the lava, and measurable crystals in phenocrysts form one-third; plagioclase is twice as abundant as the calfemic minerals. It is estimated that about one-half the latter are in measurable crystals, the remainder being in the groundmass.

Chemical composition.—The analysis of the perfectly fresh type specimen (1874) gave the following results:

Chemical analyses of hypersthene dacite and pyroxene dacite of Kendrick Peak.

	1		2
	Per cent.	Molecular ratio.	
SiO_2	60.40	1.007	61.96
Al_2O_3	17.01	.166	17.04
Fe_2O_3	2.05	.013	2.71
FeO	3.92	.054	2.66
MgO	2.97	.074	2.41
CaO	4.45	.079	3.99
Na_2O	3.85	.062	4.00
K_2O	2.97	.032	3.10
H_2O+	.70	....	.89
H_2O-	.11	....	.21
CO_2	None.	....	None.
TiO_2	1.00	.012	.87
P_2O_5	.22	.002	.22
SO_3	None.	....	None.
Cl	Trace.	....	Trace.
MnO	Undet.	....	Trace.
BaO	Undet.	....	Undet.
	99.65	....	100.06

1. Hypersthene dacite, Kendrick Peak, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.75.
2. Pyroxene dacite, Kendrick Peak.

The lava is very similar to the pyroxene dacite of the preceding stage of eruption of Kendrick Peak, as may be seen by comparing the analyses in the table. It is, however, slightly more basic in composition, as shown by the lower silica and alkalies and higher total iron, magnesia, lime, and titania. It also resembles the type latite but is low in alkalies.

Mineral composition.—The mode of the lava is as follows:

Modes of dacite of Kendrick Peak, of type dacite, and of type latite.

	1	2	3	4	5
Quartz	12.8	19.5	6.4	− 6.7	+ 6.4
Orthoclase	17.8	22.0	25.1	− 4.2	− 7.3
Albite	20.5	19.6	25.7	+ 0.9	− 5.2
Andesine (Ab_1An_1)	....	21.2	....	....	....
Andesine (Ab_4An_5)	....	....	23.0	....	....
Labradorite (Ab_3An_4)	26.8	....	....	+ 5.6	+ 3.8
Hornblende	....	10.0	12.0	+ 2.0	+ 0.4
Augite	5.0	....	....		
Hypersthene	9.4	3.6	2.1		
Magnetite	4.4	3.3	4.4		
Apatite	.5	.4	.4		
Alumina, excess of	1.6	....	....	....	....
Water	.8	.8	.8	....	....
	99.6	100.4	99.9	+ 8.5 −10.9	+10.6 −12.5

1, Mode of dacite of Kendrick Peak; 2, mode of type dacite; 3, mode of type latite; 4, departures of mode 1 from mode 2; 5, departures of mode 1 from mode 3.

The mode of this dacite has been calculated in the same manner as that of the pyroxene dacite of Kendrick Peak. The composition of the orthorhombic pyroxene obtained by calculation is: SiO_2, 54.4; FeO, 20.8; MgO, 24.8, total, 100. It is an iron-rich hypersthene in which FeO : MgO :: 1 : 2.1. As compared with the pyroxene dacite of Kendrick Peak, which has been previously described, the difference in the composition of the orthorhombic pyroxene evidently depends on differences in the relative amounts of ferric and ferrous iron in the two lavas. This difference and the more basic composition of the plagioclase were probably caused by some variation in the physical conditions under which the lavas were erupted. As may be seen from the departures given in columns 4 and 5 of the table, the lava bears a slightly closer resemblance to the type dacite than to the type latite. As compared with the type dacite, quartz and orthoclase are low and plagioclase is high, but as compared with the latite, quartz is high and alkali feldspars are low. The lava is classified simply as a hypersthene dacite.

No. 15. HORNBLENDE DACITE (DACOSE, II.4.2.4).

Occurrence.—Hornblende dacite forms the main part of O'Leary Peak and covers a small area to the south and west.

Megascopic characters.—The lava in general is compact and light gray, pink, or lilac in color; in some places medium to dark gray. The groundmass is invariably aphanitic and contains phenocrysts of feldspar and hornblende with a very small amount of quartz. The feldspar is in white and glassy idiomorphic prisms, which range from 1 millimeter to 1.5 centimeters in length, the average being about 3 millimeters. It varies in amount between 10 and 25 per cent. The larger individuals may be recognized as plagioclase. Hornblende is present in less amount and is not very noticeable on account of the small size of the crystals.

Microscopic characters.—The groundmass ranges from hypohyaline to hypomicrocrystalline, the latter being more common. It consists predominantly of feldspar, with a smaller proportion of hornblende, magnetite, and a mineral having a high index of refraction, generally showing parallel extinction, which is presumably an orthorhombic pyroxene. The color of the groundmass in the type specimen (2373), as seen under low powers, is decidedly brownish on account of the many microscopic dark-colored crystals that in part compose it.

Andesine (Ab_4An_5), hornblende, and pyroxene occur as phenocrysts. The andesine is in idiomorphic prisms, which are generally fresh, but commonly have rounded ends and are in some specimens much corroded. The crystals vary much in size and amount, as observed megascopically. The average composition is placed at Ab_4An_5, but the number of determinable crystals is too small to insure satisfactory results unless the composition is very uniform. In the lava from the summit saddle and south side of the mountain the plagioclase shows a tendency to collect in clusters having a maximum of 12 crystals and measuring 3 millimeters in diameter.

The characteristic dark phenocryst is brown hornblende in automorphic prismoids, few of which exceed 1 millimeter in length. In the type specimen the crystals are essentially unaltered, but in the lava from the summit and south foot of the mountain they are completely changed to a dull, opaque mass, though without any staining of the groundmass. Only a few phenocrysts of augite and hypersthene occur. Magnetite in fresh crystals is present in small amount, as is apatite.

Crystallinity of lava.—The micrometric analysis of the type slide (2373) gave the following results:

Micrometric analysis of hornblende dacite of O'Leary Peak.

	Composition by weight.		Average size of crystals (millimeter).
Groundmass	78.5	89.2	....
Andesine	10.7		0.22
Hornblende	7.1	10.8	.06
Pyroxene	1.4		.08
Ore	2.3		.03
		100.0	....

The groundmass is the dominant feature, as it constitutes over three-quarters of the lava. Measurable crystals of andesine and dark minerals are present in equal amount. The amount of the dark minerals shown by the analysis is considerably less than the total, because they occur also in the groundmass, and the same is presumably true of the plagioclase.

Chemical composition.—The analysis of the type specimen (2373), from the west base of the mountain, gave the following results:

Chemical analyses of hornblende dacite of O'Leary Peak, and of type dacite and type latite.

	1		2	3
	Per cent.	Molecular ratio.		
SiO_2	62.34	1.039	65.3	59.4
Al_2O_3	16.40	.161	15.1	17.6
Fe_2O_3	2.87	.018	2.6	3.3
FeO	3.32	.046	2.6	3.1
MgO	2.10	.052	2.1	2.2
CaO	3.83	.068	3.5	4.2
Na_2O	4.26	.069	3.6	4.3
K_2O	3.25	.035	3.7	4.3
H_2O+	.62		1.0	1.0
H_2O-	.08			
CO_2	None.			
TiO_2	.96	.012	.5	.5
P_2O_5	.20	.001	.2	.2
SO_3	None.			
Cl	Trace.			
MnO	Undet.		.1	.1
BaO	Undet.			
	100.23		100.3	100.2

1. Hornblende dacite, O'Leary Peak, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.59.
2. Type dacite.
3. Type latite.

The lava of O'Leary Peak resembles both the type dacite and the type latite. On the basis of chemical composition alone it is difficult to say how the rock should be classified. It may be considered a basic dacite or an acidic latite.

Mineral composition.—The mode of the lava is as follows:

Modes of dacite of O'Leary Peak, of type dacite, and of type latite.

	1	2	3	4	5
Quartz	13.2	19.5	6.4	−6.3	+6.8
Orthoclase	19.5	22.0	25.1	−2.5	−5.6
Albite	24.7	19.6	25.7	+5.1	−1.0
Andesine (Ab_4An_5)	25.6		23.0	+4.4	+2.6
Andesine (Ab_1An_1)		21.2			
Hornblende	7.0	10.0	12.0	−0.5	−2.1
Hypersthene	4.3	3.6	2.1		
Magnetite	5.2	3.3	4.4		
Apatite	.3	.4	.4		
Water	.5	.8	.8		
	100.3	100.4	99.9	+9.5 −9.3	+9.4 −8.7

1, Mode of dacite of O'Leary Peak; 2, mode of type dacite; 3, mode of type latite; 4, departures of mode 1 from mode 2; 5, departures of mode 1 from mode 3.

The amount of hornblende in the mode of the lava of O'Leary Peak is taken from the micrometric analysis, and the composition used is that of the mineral from the quartz monzonite at Walkerville station, Butte, Mont.[1] The rest of the ferric iron and titania, with an equal number of molecules of ferrous iron, forms magnetite and ilmenite. The remaining magnesia and ferrous iron, with an appropriate amount of silica, compose hypersthene in which FeO : MgO :: 1 : 3. The other oxides form the salic minerals. The amounts of plagioclase, hypersthene, and magnetite in the mode confirm the impression derived from the micrometric analysis that these minerals are largely in the groundmass.

The lava is distinctly salic, as the feldspars alone form over two-thirds of the mode. The sums of the departures from the type dacite and type latite are practically identical, and consequently the position of the lava is indeterminate. It is classified as a hornblende dacite

[1] Bull. U. S. Geol. Survey No. 228, 1904, p. 132.

because it has the same texture as the typical dacites of the region, and this texture is distinctly different from that of the latites proper.

THE LATITIC LAVAS.

OCCURRENCE AND GENERAL CHARACTER.

The lavas which are classified as latites occur at San Francisco and Mormon mountains. They are closely related and approach most nearly to the type latite. These lavas, as the name implies, are intermediate between andesites and trachytes and have the same characteristic predominance of soda over potash that is shown by the dacitic and rhyolitic lavas. They are composed of the same minerals as the dacites, but are distinguished from the dacites by lower quartz and higher albite and calfemic minerals.

No. 16. PYROXENE LATITE (TONALOSE-ANDOSE, II.4,5.3.4).

Occurrence.—Pyroxene latite, so far as observed, forms the entire mass of Mormon Mountain, except the small dacite knob on the southwest side.

Megascopic characters.—The lava is a light to medium gray and drab felsite. It contains, however, some phenocrysts of pyroxene, few of them over 2 millimeters in length. It has a marked thin-platy flow structure and in general appearance greatly resembles the lava of Crater Hill and Observatory Mesa, near Flagstaff, and also some phases of the pyroxene-hornblende latite of San Francisco Mountain.

Microscopic characters.—The lava is hypohyaline to hypomicrocrystalline. The component minerals, where recognizable, are feldspars, pyroxene, and magnetite. The first two have a parallel arrangement and in the most highly crystallized lavas tend to develop a trachytic texture. The feldspar is in slender laths, few of them over 0.15 millimeter in length. It is predominantly plagioclase of the composition Ab_1An_1 and albite. The pyroxene is also in slender laths which have an average length of about 0.05 millimeter, the maximum being 0.15 millimeter. It is mostly of an orthorhombic variety, which the mode shows to be hypersthene. A minor amount of monoclinic pyroxene, probably diopside, is present. Magnetite occurs in small amount in crystals which have a maximum diameter of 0.02 millimeter. In the more glassy lavas, where the feldspar has not extensively crystallized, the pyroxene and magnetite are prominent as a diversely arranged mat of crystals embedded in a brownish matrix.

Phenocrysts are practically lacking, although some hornblende and diopside, in idiomorphic crystals up to 0.5 millimeter and 2 millimeters, respectively, in length, are present. The hornblende is generally completely altered to a dull-black opaque mass, but some crystals have a small central portion of fresh mineral. The diopside is always fresh.

Chemical composition.—The analysis of the type specimen (2385), from the west side of the summit of the mountain, gave the following results:

Chemical analyses of pyroxene latite of Mormon Mountain and of type latite.

	1		2
	Per cent.	Molecular ratio.	
SiO_2	61.60	1.026	59.4
Al_2O_3	17.34	.170	17.6
Fe_2O_3	2.22	.014	3.3
FeO	2.73	.038	3.1
MgO	2.46	.062	2.2
CaO	4.92	.088	4.2
Na_2O	5.10	.082	4.3
K_2O	2.16	.023	4.3
H_2O+	.51	....	1.0
H_2O-	.12	....	....
CO_2	None.	....	....
TiO_2	.73	.009	.5
P_2O_5	.24	.002	.2
SO_3	None.	....	....
Cl	Trace.	....	....
MnO	Undet.	....	.1
BaO	Undet.	....	....
	100.13	....	100.2

1. Pyroxene latite, Mormon Mountain, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.63.
2. Type latite.

The analysis shows the lava to be one of medium composition, the silica, alumina, and soda being a little above and the other oxides a little below the values for the average igneous rock of the earth's crust. The lava is, however, more acidic in character than the average igneous rock and approaches most closely the type latite in composition. The slightly higher lime and especially the low potash give the rock an andesitic cast, but the high soda is a distinctly trachytic feature. The ratio of potash to soda (1 : 3.6) is the greatest found in the rocks of the region except those of a basaltic nature. This same characteristic is seen in the soda dacite of Mormon Mountain, which has a higher ratio of potash to soda than any of the other dacites of the region. It is, in fact, generally true that the lavas of each volcano possess a certain individuality which distinguishes them chemically from the corresponding lavas of the other volcanoes, although they all show a regional similarity.

Mineral composition.—The calculated mineral composition is as follows:

Modes of latite of Mormon Mountain and of type latite.

	1	2	3
Quartz	10.4	6.4	+ 4.0
Orthoclase	12.8	25.1	−12.3
Albite	25.5	25.7	− 0.2
Andesine (Ab_4An_5)	....	23.0	....
Andesine (Ab_1An_1)	35.0	....	+12.0
Hornblende [a]	2.0	12.0	
Hypersthene	5.4	2.1	
Diopside [a]	3.7	....	− 2.8 (Hornblende to apatite, bracketed)
Magnetite	4.4	4.4	
Apatite	.6	.4	
Water	.6	.8	....
	100.4	99.9	+16.0 / −15.3

[a] Hornblende from quartz monzonite, Walkerville station, Butte, Mont., and diopside of average composition (SiO_2, 52; Al_2O_3, 1; Fe_2O_3, 2; FeO, 4; MgO, 17; CaO, 21; other oxides, 3; total, 100) used on mode of lava of Mormon Mountain.

1, Mode of latite of Mormon Mountain; 2, mode of type latite; 3, departures of mode 1 from mode 2.

The amount of hornblende is estimated from thin sections. The amount of diopside is obtained by adjustment, so that no excess of alumina remains. The composition of the orthorhombic pyroxene obtained from calculating the mode is: SiO_2, 55.8; FeO, 14.7; MgO, 29.5; total, 100. This is a hypersthene in which Fe : Mg is nearly 1 : 3. The lava is decidedly salic, as the feldspars alone constitute three-quarters of the mode. As compared with the type latite orthoclase is low and andesine is high, which shows the andesitic cast of the rock. It is classified simply as a pyroxene latite.

No. 17. PYROXENE-HORNBLENDE LATITE (DACOSE-AKEROSE-TONALOSE-ANDOSE, II.4,5.2,3.4).

Occurrence.—Pyroxene-hornblende latite, either as lava or as fragmental material, is well exposed in the lower part of the walls of the large interior valley of San Francisco Mountain and a considerable mass also occurs on the east side of the mountain.

Megascopic characters.—The lava shows a wide range of colors, including light lilac, red, brown, and medium to dark gray. The groundmass is aphanitic and contains from 10 to 20 per cent of lath-shaped feldspar phenocrysts which average between 2 and 3 millimeters in length, few of them exceeding 5 millimeters. They generally have a fluidal (parallel) arrangement. Dark minerals are practically lacking, although in some flows rust spots indicate their former presence.

Microscopic characters.—The groundmass varies from hypohyaline to hypomicrocrystalline in which the glassy base constitutes from 10 to 20 per cent. In the latter varieties it consists predominantly of slender feldspar laths, few of which are over 0.05 millimeter in length, and where these are sufficiently abundant they give rise to a trachytic texture. They are orthoclase, albite, and plagioclase of a composition between Ab_1An_1 and Ab_3An_4. Quartz is not ordinarily present, but a few crystals have separated out in the most highly crystalline lavas. Considerable numbers of minute colorless, brown, and black crystals, which are, in all probability, pyroxene, hornblende, and magnetite, are also present.

Plagioclase of a composition between Ab_1An_1 and Ab_3An_4, augite, hypersthene, and hornblende occur as phenocrysts. The plagioclase is in automorphic prismoids from megascopic sizes to lath-shaped individuals less than 0.1 millimeter in length. The larger crystals are very commonly corroded and presumably represent an early generation, whereas the smaller fresh crystals belong to the period of general crystallization.

In all specimens the calfemic minerals are present in small amount. Pyroxene occurs more generally than hornblende and should be considered the characteristic dark component. Augite in fresh subhedral crystals predominates over hypersthene. Hornblende, however, may replace the pyroxene, as in the type specimen (1803). It is the common brown variety and occurs in more or less altered automorphic prismoids having a maximum length of 1 millimeter. Measurable crystals of magnetite occur only in very small amount, as does apatite.

Crystallinity of the lava.—The micrometric analysis of the type specimen (1803), from the foot of the inner (southeast) slope of San Francisco Peak, gave the following results:

Micrometric analyses of pyroxene hornblende latite of San Francisco Mountain.

	Composition by weight.		Average size of crystals (millimeter).
Groundmass	81.4	96.2	
Plagioclase (Ab_4An_5)	14.8		0.40
Hornblende	1.1	3.8	.20
Augite	.5		.23
Ore	2.2		.08
	100.0		

The groundmass is the dominating physical feature of the lava. Though the analysis pictures with reasonable accuracy the crystallinity of the lava, it gives only a slight idea of its mineral composition. The measurable dark minerals constitute only about one-fifth the total amount, the remainder being in the groundmass with the salic minerals. The groundmass, it will be recalled, includes all minerals whose average size is less than 0.01 millimeter. From a study of thin sections it is probable that the lava would be classified as more salic (acidic) in composition than it actually is.

Chemical composition.—The analysis of the type specimen (1803) gave the following results:

Chemical analyses of pyroxene-hornblende latite of San Francisco Mountain, of type latite, and of average igneous rock.

	1		2	3
	Per cent.	Molecular ratio.		
SiO_2	59.76	0.996	59.4	57.8
Al_2O_3	17.03	.166	17.6	15.7
Fe_2O_3	5.99 / [a] 3.0	.037	3.3	3.3
FeO	.90 / [a] 3.6	.013	3.1	3.8
MgO	2.11	.053	2.2	3.8
CaO	4.06	.072	4.2	5.2
Na_2O	4.50	.073	4.3	3.9
K_2O	2.94	.031	4.3	3.1
H_2O+	.43		1.0	1.4
H_2O-	.64			.4
CO_2	None.			
TiO_2	1.07	.013	.5	1.0
P_2O_5	.35	.002	.2	.4
SO_3	None.			
Cl	Trace.			
MnO	.10	.001	.1	.2
SrO	.03			
BaO	.14	.001		
	100.05		100.2	100.0

[a] Corrected value for fresh rock.

1. Pyroxene-hornblende latite, San Francisco Mountain, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.69.
2. Type latite.
3. Average igneous rock of earth's crust. Washington, H. S., Prof. Paper U. S. Geol. Survey No. 14, 1903, p. 108.

The lava is of medium composition with respect to all the oxides and is not far removed from the average igneous rock of the earth's crust. Except for lower potash, it approaches very closely to the type latite, and may be classified as latite on the basis of chemical composition. The iron is almost entirely in the ferric condition on account of the alteration of the calfemic minerals. Corrected values for the fresh rock, obtained in calculating the mode, are given in the table.

The lava classifies in the quantitative system as tonalose-andose, being on the border of the orders austrare and germanare, when the values for ferric and ferrous iron determined by analysis are used. This suggests too andesitic a character for the rock. If the corrected values for the iron are used, it classifies as dacose-akerose-tonalose-andose, being on the border not only between the orders austrare and germanare, but between rangs 2 and 3. This position gives a much better idea of the composition.

Mineral composition.—Two modes are given in which hornblende and pyroxene are the characteristic calfemic minerals. The latter is the more common. The results are as follows:

Modes of latite of San Francisco Mountain and type latite.

	1	2	3	4
Quartz	11.2	11.7	6.4	+5.3
Orthoclase [a]	17.5	17.5	25.1	−7.6
Albite	27.6	28.2	25.7	+2.5
Andesine (Ab_4An_5)	21.6	22.5	23.0	−0.5
Hornblende [b]	10.8	....	12.0	
Hypersthene [b]	3.0	5.2	2.1	
Augite [b]	....	5.0	....	−1.3
Magnetite	5.3	6.6	4.4	
Apatite	.8	.8	.4	
Alumina, excess of	1.4	1.5	....	....
Water	.8	1.1	.8	....
	100.0	100.1	99.9	+7.8 / −9.4

[a] Orthoclase contains 0.3 per cent of hyalophane.

[b] Hornblende from quartz monzonite, Walkerville station, Butte, Mont.; augite from monzonite, Monzoni (Iddings, J. P., Rock minerals, 1906, p. 298); and hypersthene in which FeO : MgO : : 1 : 2.4 in hornblende mode, 1 : 2.7 in pyroxene mode, used in modes of latite of San Francisco Mountain.

1, Mode of hornblende latite of San Francisco Mountain; 2, mode of pyroxene latite of San Francisco Mountain; 3, mode of type latite; 4, departures of mode 2 from mode 3.

The amount of hypersthene in the hornblende mode is placed at 3 per cent. The remaining magnesia then governs the quantity of hornblende, and the iron, titania, and manganous oxide left form magnetite and ilmenite. The salic minerals are composed of the oxides that remain after the calfemic minerals are calculated. It is evident that considerable hypersthene must be present in the pyroxene mode, as otherwise the requisite amount of plagioclase would not be obtained. If augite dominated over hypersthene, as does hornblende, the lava would contain only about 6 per cent of plagioclase, which is far from correct, and there would be an excess of some 5 per cent of alumina. The augite is placed at a figure that gives the proper amount of plagioclase, as indicated by the micrometric analysis. Aside from the calfemic minerals the two modes are very similar, as may be seen in the table. The lava is decidedly salic, as the feldspars alone form over two-thirds the total in each mode. As compared with the type latite quartz is high and orthoclase low, thus showing the andesitic cast of the lava. As either pyroxene or hornblende may be the dominant calfemic mineral, the lava is classified as a pyroxene-hornblende latite.

THE ANDESITIC LAVAS.

OCCURRENCE AND GENERAL CHARACTER.

Lavas belonging to this group occur at San Francisco Mountain, Kendrick Peak, and Bill Williams Mountain. Those at the first two localities approach closely to the type andesite in composition. That at Bill Williams Mountain is more basic and is classified as an andesite-basalt. They all exhibit the characteristic chemical feature of the lavas of the San Franciscan region in having a greater predominance of soda over potash than is found in the type rock.

In addition, the lava of San Francisco Mountain has lower magnesia and lime, which is a feature peculiar to all the lavas of that volcano. The hornblende-soda andesite-basalt, it may be noted, has an abnormal mineral composition, because it is genetically related to the dacites and occurs as secretions in those lavas at Bill Williams and San Francisco mountains and O'Leary Peak.

No. 18. AUGITE ANDESITE OF SAN FRANCISCO MOUNTAIN (ANDOSE, II.5.3.4).

Occurrence.—Augite andesite is, in part, the surface rock of the upper slopes of San Francisco Mountain. It also forms the surface of the lower southwest slope and to a less extent outcrops at the eastern base of the mountain. It occurs as an intrusive rock in the vent and in dikes.

Megascopic characters.—The lava is medium to very dark gray in color, locally mottled with brownish specks, the darker tones predominating. It is generally compact but in part finely vesicular and commonly has a basaltic texture. Phenocrysts of feldspar, few of them over 1 millimeter in length, are present in variable amounts from almost nothing up to 20 per cent. In some specimens small iridescent crystals of olivine occur, but they are more generally lacking. The intrusive rock is texturally the same as the extrusive but is generally lighter colored and the feldspar phenocrysts tend to occur in larger crystals, the maximum length being 8 millimeters. The core rock differs most strikingly from the lava in mass by having a thin platy and rude columnar structure. (Pl. VIII, *B*, p. 43.)

Microscopic characters.—The lava consists of varying amounts of feldspar, pyroxene, olivine, and magnetite in a brownish groundmass of hyaline to cryptocrystalline texture. There was but one stage of crystallization and the minerals separated out in the reverse of the order above given. The crystallized minerals generally constitute from 25 to 75 per cent of the lava; holomicrocrystalline textures are rare. This feature is illustrated by the micrometric analyses given below. The lava is essentially nonporphyritic, as seen in thin section. The minerals are for the most part automorphic prisms with a fluidal arrangement, which is more especially noticeable in those specimens having the least groundmass. In the lavas which have the greatest abundance of crystallized minerals a pilotaxitic structure tends to develop.

The feldspar occurs in lath-shaped crystals whose ratio of width to length is about 1:4. They range in length from a few hundredths of a millimeter to 1 millimeter. In the type specimen 1829 the crystals which give the texture its character average about 0.3 millimeter. The feldspar is predominantly a plagioclase of the composition Ab_3An_4. None more basic than that were observed, but those as acidic as Ab_1An_1 are not uncommon and occur as a secondary growth about many of the more basic individuals. The average composition of the plagioclase as a whole is placed at Ab_7An_9. In the lavas which have the least amount of groundmass albite is also present in considerable quantity.

The pyroxene is mostly augite in slender automorphic prisms, few of them over 1 millimeter in length. Parallel extinction in some of the prismatic sections may indicate either augite cut parallel to 100 or hypersthene; the calculated mode of the lava shows that the latter mineral must be present in small amount. Olivine is also present in characteristic diamond-shaped or rounded sections up to 0.5 millimeter in length. Magnetite is next in abundance to pyroxene among the calfemic minerals and was the first to crystallize, as shown by inclosure in the later minerals. The sections are rarely over 0.15 millimeter in diameter. Apatite occurs in very small amount.

Crystallinity of lava.—The wide range in the relative amounts of groundmass and measurable crystals, those whose average diameter is greater than 0.01 millimeter, is shown by the following micrometric analyses:

Micrometric analyses of augite andesite of San Francisco Mountain.

	1	2	3	Average size of crystals (millimeter).		
				1	2	3
Groundmass	27.7	47.7	66.6	0.03	0.06	0.10
Feldspar	52.9	40.2	22.0	.06	.06	.04
Pyroxene	10.4	3.3	3.4	.02	.02	.02
Olivine	2.4	2.5	2.1	.10	.03	.06
Magnetite	6.6	6.3	5.9	.02	.02	.02
	100.0	100.0	100.0	.04	.04	.03

1. Type specimen 1829, south slope of peak F, elevation 10,000 feet.
2. Specimen 2129, northeast slope of peak C, near summit.
3. Specimen 2110, north slope of San Francisco Peak, elevation 12,000 feet.

The analyses bring out clearly several features that would very probably otherwise escape recognition. The ore and olivine have most probably entirely crystallized out from the magma, as they are present in constant amount in all three specimens, the differences shown falling within the errors of observation. Their amount, therefore, is independent of the degree of crystallinity shown by the groundmass or feldspars. The same relation holds true of the size of the ore grains, for it is constant in all three specimens. The size of the olivine crystals, on the contrary, is exceedingly variable and exhibits no relation to the crystallinity of the lava. This is due to the wide range in the size of the crystals and the small amount in which they are present. The pyroxene is much more abundant in specimen 1829 than in the other two, the difference being too great to be accounted for by errors in measurement. It may be stated, therefore, that this mineral appears to entirely separate out only where the groundmass constitutes less than one-half the rock. The size of the crystals, however, is practically constant in all the specimens, and may be considered as independent of the crystallinity of the lava.

The groundmass and feldspar exhibit an inverse relationship. As the former increases in amount, the latter decreases in nearly equal proportion; the difference between extreme values is 58 per cent for each. The size of the feldspars is smallest in the lava containing the largest amount of groundmass and greatest in that containing the least, but the relation is not regular. A maximum size is developed when the groundmass constitutes less than one-half the lava. The figures for the groundmass represent the average distance between crystals; it increases, of course, as the number of crystals decreases. In specimen 1829 the distance is but half the average size of the feldspars, and the groundmass consequently is largely interstitial in character. In specimen 2110, on the contrary, the distance is greater than the average size of all the crystals, and the groundmass so exceeds the crystals in amount that it entirely surrounds them.

Micrometric analyses, such as these, are very useful in presenting a definite idea of the crystallinity of a rock. They also illustrate, in this case, the difficulty of classifying a lava from study of a thin section. Specimen 1829, in which about three-quarters of the minerals have crystallized, could be classified with some certainty as an andesite, although all the quartz and orthoclase are in the groundmass. Specimen 2110, however, contains so little crystallized material in recognizable sizes that it could not well be placed from an inspection only of the thin section. A chemical analysis is therefore necessary in order to obtain satisfactory results, and this is true of all the lavas of the region.

Chemical composition.—The analysis of the perfectly fresh type specimen (1829), from the south slope of peak F, gave the following results:

Chemical analyses of augite andesite of San Francisco Mountain, of type andesite, and of pyroxene andesite from Colombia, South America.

	1		2	3
	Per cent.	Molecular ratio.		
SiO_2	57.64	0.961	57.2	56.91
Al_2O_3	17.07	.168	16.7	18.18
Fe_2O_3	3.07	.019	3.7	4.65
FeO	5.15	.072	4.1	3.61
MgO	2.80	.070	3.9	3.49
CaO	5.55	.099	6.4	7.11
Na_2O	4.20	.068	3.5	4.02
K_2O	2.14	.023	2.3	1.61
H_2O+	.05		1.3	.36
H_2O-	.09			
CO_2	None.			
TiO_2	1.57	.019	.7	
P_2O_5	.37	.003	.2	.25
SO_3	None.			
Cl	Trace.			
MnO	.08	.001	.2	
SrO	None.			
BaO	.05			
	99.85		100.2	100.19

1. Augite andesite, San Francisco Mountain, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.74.
2. Type andesite.
3. Pyroxene andesite, Colombia, South America. (Küch, R., Geologische Studien in der Republik Colombia, in Reiss and Stübel, Reisen in Süd Amerika, Band 1, 1892, p. 139.)

The analysis shows that the lava approaches closely the type andesite in composition and also the pyroxene andesite of Pasto Volcano, in Colombia, South America. As compared with the type it has higher ferrous iron, lower magnesia and lime, and a higher ratio of potash to soda. It thus exhibits the characteristic features of the lavas of San Francisco Mountain, which have already been observed in the more acidic members.

Mineral composition.—The complete mineral composition is calculated as follows:

Calculated mineral composition of augite andesite of San Francisco Mountain.

	Per-centage.	SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	MgO.	CaO.	Na_2O.	K_2O.	H_2O+.	H_2O-.	TiO_2.	P_2O_5.	MnO.	BaO.
Percentage		57.64	17.07	3.07	5.15	2.80	5.55	4.20	2.14	0.05	0.09	1.57	0.37	0.08	0.05
Apatite	1.0						.56						.37		
Magnetite	4.2			2.91	1.34									.02	
Ilmenite	2.7				1.30							1.40			
Olivine	2.4	.92			.59	.92								.01	
Hypersthene	3.6	1.86			.96	.68								.01	
Augite	8.0	3.62	.64	.16	.96	1.20	1.12					.20		.04	
Sum		6.40	.64	3.07	5.15	2.80	1.68					1.60	.37	.08	.05
Remainder		51.24	16.45				3.87	4.20	2.14	.05	.09				.05
Molecular ratios		0.854	.161				.069	.068	.024						
Orthoclase	13.1	.140	.024						[a] .024						
Albite	35.6	.408	.068					.068							
Anorthite	19.2	.138	.069				.069								
Quartz	10.1	.168													

[a] BaO is put in with K_2O as equal to 1 molecule, carrying 1 molecule Al_2O_3 and $2SiO_2$.

Ratio of MgO: FeO in olivine is 3:1; in hypersthene, 1:0.76.
Augite: SiO_2, 46.5; Al_2O_3, 8.0; Fe_2O_3, 2.0; FeO, 12.0; MgO, 15.0; CaO, 14.0; TiO_2, 2.5; total, 100.0.

In order to use all the ferrous iron it is necessary to suppose that the olivine, hypersthene, and augite are rich in that constituent. The amount of olivine is taken from the micrometric analysis. Magnetite and ilmenite take all the ferric iron and titania, with their proportionate ferrous iron content, left after calculating the augite. The amount (6.9 per cent) agrees well with that measured (6.6 per cent). It is evident that not all the pyroxene is augite, for in that event insufficient lime would remain for anorthite, and there would be an excess of alumina. The composition of the augite has been chosen to meet this condition. The amount of augite is placed at 8 per cent, which leaves just enough lime, in connection with the alkalies, to satisfy the alumina. The ferrous iron and magnesia that remain are then put into hypersthene. How close the assumed composition of the dark minerals agrees with their actual composition can not be stated, as none of them have been analyzed. It may be said in favor of the assumed compositions that they give amounts of dark minerals which agree closely with those of the micrometric analysis and are in no way unusual.

The mode of the lava is as follows:

Modes of andesite of San Francisco Mountain, of type andesite, and of pyroxene andesite of Colombia, South America.

	1	2	3	4	5
Quartz	10.1	80.6	9.6	8.9	+ 0.5
Orthoclase	13.1		13.3	9.4	— 0.2
Albite	20.7		8.5	14.9	+12.2
Andesine (Ab_7An_9)	34.1		....	43.9	— 7.5
Andesine (Ab_1An_1)	....	....	41.6	....	....
Augite	8.0	10.4	10.0	14.0	— 3.8
Hypersthene	3.6		9.0	....	
Olivine	2.4	2.4	....	....	
Magnetite	6.9	6.6	6.3	8.5	
Apatite	1.0	....	.4	.3	
Water	.1	....	1.3	.3	....
	100.0	100.0	100.0	99.9	+12.7 −11.5

1, Mode of andesite of San Francisco Mountain; 2, micrometric analysis of same lava; 3, mode of type andesite; 4, mode of pyroxene andesite, Pasto Volcano, Colombia, South America; 5, departures of mode 1 from mode 3.

The similarity of the lava of San Francisco Mountain to the type andesite and to the andesite of Colombia is apparent. As compared with the type, albite, in particular, is high and plagioclase low, partly because of the more acidic composition of the plagioclase. The lava is classified simply as an augite andesite.

The micrometric analysis is given to show the extent of agreement between it and the calculated mode. The olivine is the same in the calculated mode by assumption; otherwise the results are independent. Apatite can not be measured in thin section, and consequently is included with the salic minerals, from which it should be deducted in making comparisons. There is a difference, then, of 1.6 per cent between the calculated and measured amounts of the salic minerals, 1.2 per cent in the pyroxene, and 0.3 per cent in the magnetite. The salic minerals are slightly greater and the calfemic minerals slightly smaller in the measured than in the calculated mode, and this is at least partly due to the presence of crystals of less than measurable size in the groundmass. The result is very satisfactory when it is considered that the average size of the crystals is but 0.04 millimeter. It should be noted that the sum of quartz and orthoclase (26.2 per cent) in the calculated mode is nearly the same as the measured amount of groundmass (27.7 per cent). Also the sum of albite and andesine (54.8 per cent) agrees closely with the measured amount of feldspar (52.9 per cent). It is thus probable, as is also shown by the calculated specific gravity (see p. 206), that quartz and orthoclase have remained uncrystallized in the groundmass.

No. 19. AUGITE ANDESITE OF KENDRICK PEAK (ANDOSE, II.5.3.4).

Occurrence.—The augite andesite here described occurs only at the summit and on the upper western slope of Kendrick Peak.

Character.—The lava is so similar, both megascopically and microscopically, to the augite andesite of San Francisco Mountain that the description of that lava may be applied to it practically without change.

Crystallinity of lava.—The measurement of the type specimen (1875), from the summit of the mountain, gave the following results:

Micrometric analysis of augite andesite of Kendrick Peak.

	Composition by weight.		Average size of crystals (millimeter).
Groundmass	32.2	85.4	....
Plagioclase phenocrysts	20.0		0.73
Feldspar	33.2		0.06
Pyroxene	7.4	14.6	.02
Olivine	4.2		.06
Ore	3.0		.01
	100.0		[a] .04

[a] Excluding phenocrysts.

On account of the small volume of lava erupted, it is probable that the analysis is fairly representative of the whole mass. The lava has about the same proportion of groundmass as the andesite of San Francisco Mountain, but differs from it in having 20 per cent of large feldspar (Ab_7An_9) phenocrysts. The average grain of the two lavas is the same, but the magnetite is smaller in the andesite of Kendrick Peak—too small, in fact, for the amount to be accurately measured. The innumerable pyroxene and ore crystals in the groundmass make it evident that only a part of the calfemic minerals is included in the measured amount of 14.6 per cent.

Chemical composition.—The analysis of the perfectly fresh type specimen (1875) gave the following results:

Chemical analyses of augite andesite of Kendrick Peak and of type andesite.

	1		2
	Per cent.	Molecular ratio.	
SiO_2	56.51	0.942	57.2
Al_2O_3	16.28	.159	16.7
Fe_2O_3	2.93	.018	3.7
FeO	5.13	.071	4.1
MgO	4.12	.103	3.9
CaO	6.10	.109	6.4
Na_2O	3.94	.063	3.5
K_2O	2.18	.023	2.3
H_2O+	.40	....	1.3
H_2O-	.10	....	....
CO_2	None.	....	....
TiO_2	1.50	.018	.7
P_2O_5	.30	.002	.2
SO_3	None.	....	....
Cl	Trace.	....	....
MnO	.08	.001	.2
BaO	Undet.	....	....
	99.57	....	100.2

1. Augite andesite, Kendrick Peak, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.77.
2. Type andesite.

Comparison of the analysis with that of the type andesite shows that the two are practically identical, and the lava of Kendrick Peak may be classified as a typical andesite.

Mineral composition.—The mode of the lava is as follows:

Modes of andesite of Kendrick Peak and of type andesite.

	1	2	3
Quartz	8.6	9.6	− 1.0
Orthoclase	12.8	13.3	− 0.5
Albite	18.6	8.5	+10.1
Andesine (Ab_7An_9)	32.8	....	− 8.8
Andesine (Ab_1An_1)	....	41.6	....
Augite	9.3	10.0	+ 0.6
Hypersthene	5.5	9.0	
Olivine	4.3	....	
Magnetite	6.5	6.3	
Apatite	.7	.4	
Water	.5	1.3	....
	99.6	100.0	+10.7 −10.3

1, Mode of andesite of Kendrick Peak; 2, mode of type andesite; 3, departures of mode 1 from mode 2.

The mode of the lava of Kendrick Peak has higher albite and lower andesine than the type andesite, owing partly to the more acidic composition of the plagioclase. The mode of the type is calculated without olivine, as theoretically it does not form in the presence of an excess of silica. Olivine and quartz, as well as other mutually exclusive minerals, do, however, actually occur together in small amounts. The lava is classified simply as an augite andesite.

No. 20. AUGITE ANDESITE-BASALT (ANDOSE, II.5.3.4).

Occurrence.—Augite andesite-basalt is exposed on the north and west sides of the main (central) dacite core and also on the south slope of Bill Williams Mountain.

Character.—The lava, in hand specimens, is dark gray in color and has a basaltic texture. It is commonly nonporphyritic, although some phenocrysts of pyroxene or olivine occur. It generally resembles the fine-grained basalts of the third general period of eruption and is distinguished from them with difficulty. In thin section, however, it clearly resembles those augite andesites of San Francisco Mountain and Kendrick Peak in which the groundmass predominates. The plagioclase is more basic, the average composition being placed at Ab_2An_3. There are very few measurable crystals of magnetite, and consequently the groundmass is filled with innumerable minute grains which give it a dark tone. The pyroxene is also almost entirely in the groundmass, and in general the lava is too fine grained to be measured.

Chemical composition.—The analysis of a lava fragment (2354) from the breccia at the north base of the central dacite core, and in which the dark minerals are slightly altered, gave the following results:

Chemical analyses of augite andesite-basalt of Bill Williams Mountain and of type andesite-basalt.

	1		2
	Per cent.	Molecular ratio.	
SiO_2	51.53	0.859	52.6
Al_2O_3	18.21	.178	16.5
Fe_2O_3	4.59 (3.8)	.029	3.9
FeO	5.46 (6.1)	.076	5.9
MgO	4.99	.125	5.6
CaO	8.05	.144	8.2
Na_2O	3.45	.056	3.2
K_2O	1.67	.018	1.7
H_2O+	.31		1.0
H_2O-	.20		.2
CO_2	None.		
TiO_2	1.50	.018	1.1
P_2O_5	.36	.003	.3
SO_3	None.		
Cl	Trace.		
MnO	.10	.001	.2
BaO	Undet.		
	100.42		100.4

1. Augite andesite-basalt, Bill Williams Mountain, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.82.
2. Type andesite-basalt.

The lava is somewhat more basic than might be expected from comparison in thin section with the andesites of San Francisco Mountain and Kendrick Peak. It has so far approached a basalt as to fall chemically midway between the type andesite and the type basalt. It may be classified, therefore, as an andesite-basalt.

Mineral composition.—The mode of the lava, in which the relative amounts of the calfemic minerals are made to approximately correspond to those in the andesites of San Francisco Mountain and Kendrick Peak, is as follows:

Modes of andesite-basalt of Bill Williams Mountain and of type andesite-basalt.

	1	2	3
Quartz	2.6	4.4	−1.8
Orthoclase	10.0	10.0	0.0
Albite	11.5	8.8	+2.7
Andesine (Ab_3An_4)	....	42.3	....
Labradorite (Ab_2An_3)	44.5	....	+2.2
Augite *a*	11.0	16.0	−2.5
Hypersthene *a*	6.7	5.7	
Olivine *a*	5.0	5.0	
Magnetite	7.6	6.4	
Apatite	1.0	.7	
Water	.5	1.0	....
	100.4	100.3	+4.9 −4.3

a Augite from basalt 6 miles northeast of Grants, N. Mex. (Bull. U. S. Geol. Survey No. 228, 1904, p. 194). Hypersthene in which FeO : MgO : : 1 : 1, and olivine in which MgO : FeO : : 3.5 : 1 used in mode of lava of Bill Williams Mountain.

1, Mode of andesite-basalt of Bill Williams Mountain; 2, mode of type andesite-basalt; 3, departures of mode 1 from mode 2.

Labradorite and calfemic minerals form three-quarters of the mode of the lava. Quartz is present in very small amount. The resemblance to the type andesite-basalt is close, although this is due partly to the more basic composition of the plagioclase. As will appear later (p. 183), magnesia and alumina have not been completely separated in the analysis of this lava. Alumina should be about 17.2 per cent and magnesia 6 per cent. This would cause some slight changes in the mode as here given. The lava is classified as an augite andesite-basalt.

No. 21. HORNBLENDE-SODA ANDESITE-BASALT (ANDOSE, II.5.3.4).

Occurrence.—Hornblende-soda andesite-basalt occurs as inclusions in the dacites of San Francisco Mountain, Kendrick Peak, Bill Williams Mountain, and O'Leary Peak. The type specimen comes from the summit of the small secondary cone on the northwest slope of Bill Williams Mountain.

Megascopic characters.—The rock is dark gray or brown in color and has a compact aphanitic or microcrystalline texture; it is commonly nonporphyritic. The type specimen, however, contains numerous diversely arranged phenocrysts of black hornblende, in slender crystals up to 1 centimeter in length, embedded in a light-gray aphanitic groundmass. Some of the inclusions are approximately spherical, but more commonly they are polyhedral in form, with subangular edges, and so far as observed their longest diameter is as a rule not more than 1 foot.

Microscopic characters.—The similarity of the inclusions from different localities is evident in thin section. They consist of a diverse arrangement of automorphic prismoids of plagioclase, ranging from Ab_3An_4 to Ab_5An_3, albite, brown hornblende with an extinction angle of 0° to 5°, magnetite, and apatite, embedded in a glassy groundmass. The groundmass is very commonly in a devitrified state, which has presumably been produced by the heat of the inclosing lava. In the type specimen some of the feldspar is slightly altered and a single band of minute inclusions indicates two stages of crystallization. The hornblende is entirely fresh, but some crystals show a small amount of resorption; it separated out before the feldspar.

Crystallinity of the rock.—The micrometric analysis of the type specimen (2384a) from Bill Williams Mountain gave the following results:

Micrometric analyses of hornblende-soda andesite-basalt from Bill Williams Mountain.

	Percentage by weight.		Average size of crystals (millimeter).
Groundmass	37.0	49.5	....
Labradorite (Ab_3An_4)	12.5		0.15
Hornblende	48.4	50.5	.50
Magnetite	2.1		.06
	100.0		....

Groundmass and hornblende compose 85.4 per cent of the type specimen. The amounts of both are, however, larger than is common; probably 20 per cent and 30 per cent, respectively, would more nearly represent the average. The amount of hornblende is noticeably variable at different localities, so that the average composition of the inclusions may be obtained only by a composite analysis. The irregular distribution of the hornblende is especially evident in the small outcrop at the type locality on account of the light color of the groundmass of the rock. The material used in making the type slide and the chemical analysis, however, came from the same small fragment of rock and may be considered as having the same composition.

Chemical composition.—The analysis of the fresh type specimen (2384a) from Bill Williams Mountain gave the following results:

Chemical analyses of rocks from Bill Williams Mountain and from Lassen Peak region, California.

	1		2	3	4	5
	Per cent.	Molecular ratio.				
SiO_2	53.97	0.900	65.99	54.11	66.07	51.53
Al_2O_3	16.00	.157	16.14	18.95	16.05	17.20
Fe_2O_3	4.56	.029	2.28	3.85	1.53	4.59
FeO	3.63	.050	1.84	3.44	2.18	5.46
MgO	6.36	.159	1.47	4.99	1.79	6.00
CaO	7.47	.134	3.57	9.26	4.15	8.05
Na_2O	4.38	.071	4.73	3.19	4.11	3.45
K_2O	1.23	.013	2.90	.92	2.43	1.67
H_2O+	1.31		.67	.71	.98	.31
H_2O-	.03		.15			.20
CO_2	None.		None.			None.
TiO_2	1.46	.018	.68	.53	.36	1.50
P_2O_5	.10	.001	.15	.11	.12	.36
SO_3	None.		None.			None.
Cl	Trace.		Trace.			Trace.
MnO	Undet.		Undet.	.16	.09	.10
BaO			Undet.	.01	.07	Undet.
SrO				.05	.02	
Li_2O					Trace.	
	100.50		100.57	100.28	99.95	100.43

1. Hornblende-soda andesite-basalt, inclusion in hornblende-soda dacite, Bill Williams Mountain, San Franciscan volcanic field, Arizona. Ralph J. Marsh, analyst.
2. Hornblende-soda dacite, Bill Williams Mountain.
3. Average composition of secretions in the dacites of the Lassen Peak region, California (analyses E, G, and X, Bull. U. S. Geol. Survey No. 228, 1904, pp. 212, 213, and 216). W. F. Hillebrand, analyst.
4. Average composition of the lavas in which the secretions of No. 3 occur (analyses D, F, and W, idem, pp. 212, 213, and 216). W. F. Hillebrand, analyst.
5. Augite andesite-basalt, Bill Williams Mountain.

As compared with the chemical composition of the lava in which it occurs, the inclusion has lower silica and potash and higher iron, magnesia, lime, and titania, whereas the alumina, soda, and phosphoric pentoxide are the same. The relatively large increase in magnesia, which is not due to any error in analysis, as the determination was made in duplicate, and the constancy of soda appear to be the most striking features. The chemical composition of the rock in a general way resembles that of the type andesite-basalt and is quite similar to that of the augite andesite-basalt, which occurs at Bill Williams Mountain and is given in column 5 for comparison.

The average composition of the secretions of the Lassen Peak region and of the dacites in which they occur is very similar to that of the corresponding rocks of Bill Williams Mountain, as may be seen by comparing the analyses given in the table. The differences between the two rocks of the Lassen Peak region are of the same character as those shown by the rocks of Bill Williams Mountain. There is the same relatively greater increase in magnesia, but soda has decreased somewhat instead of remaining constant. The secretions of the two regions are so similar that they must have originated under the same conditions.

Mineral composition.—The calculated mode of the Bill Williams rock is given below:

Modes of various rocks of Bill Williams Mountain and of type andesite-basalt.

	1	2	3	4	5
Quartz	7.1	18.7	11.9	2.6	− 4.8
Orthoclase	4.4	16.2	8.3	10.	− 3.9
Albite	23.8	26.3	3.1	11.5	+20.7
Andesine (Ab_1An_1)		26.2			
Labradorite (Ab_3An_4)	14.2		34.4		−20.2
Labradorite (Ab_2An_3)				44.5	
Hornblende	47.6	6.2	35.0		+ 8.0 (Hornblende to Apatite)
Biotite		1.9			
Augite				11.0	
Hypersthene		.9		6.7	
Olivine				5.0	
Magnetite	2.0	3.1	6.2	7.6	
Apatite	.3	.4	.7	1.0	
Water	1.3	.6	.9	.5	
	100.7	100.5	100.5	100.4	+28.7 −28.9

1, Mode of secretion in soda dacite of Bill Williams Mountain; 2, mode of soda dacite in which secretion occurs; 3, mode of type hornblende andesite-basalt; 4, mode of augite andesite-basalt of Bill Williams Mountain; 5, departures of mode 1 from mode 3.

The amount of magnetite in the mode is taken from the micrometric analysis and is assumed to be made up of 6 molecules of magnetite and 4 molecules of ilmenite. The rest of the iron and titania and all the magnesia go into hornblende. The amounts of the other constituents of the hornblende are obtained from a mineral of average composition, based on analyses Nos. 100–119 of aluminous hornblendes in Dana's Mineralogy (pp. 395–396), which furnishes the following ratios: $MgO:SiO_2::1:2.1$; $MgO:Al_2O_3::1:0.37$; $MgO:CaO::1:0.64$; $MgO:Na_2O::1:0.09$; $MgO:K_2O::1:0.03$. After the apatite and hornblende are calculated there is an excess of 4 molecules of alumina over the sum of lime and alkalies, which is eliminated by putting it into hornblende. The feldspars are then figured out on the basis of their theoretical composition and there remains a final excess of 118 molecules of silica. An idea of the accuracy of the results may be gained by comparison with the micrometric analysis. The calculated amount of hornblende is 47.6 per cent, as against 48.4 per cent measured. The total amount of the calculated salic minerals (49.5 per cent) is the same as that measured. Magnetite is the same by assumption. The agreement is surprisingly close considering the manner in which the composition of the hornblende is obtained and indicates that the latter must be very close to the true composition of the mineral in the secretion.

The secretion is composed of essentially the same minerals as the soda dacite in which it occurs, but it is very much more calfemic in character, as may be seen from the modes in the table. Albite alone, of the important constituents, approaches the amount in the inclosing lava. It is interesting to observe that the secretion has not only the same minerals, but also the same texture as the lava in which it occurs.

The modes of the secretion and the type andesite-basalt, with hornblende as the chief calfemic mineral (column 4), show a wide divergence in the amounts of albite and plagioclase which is largely brought about by the greater amount of hornblende in the secretion. If the hornblende were nearer the average amount (30 per cent) that occurs in the secretions, a considerable quantity of lime would be set free which would go into the anorthite molecule, thus increasing the plagioclase and decreasing the albite. In general the resemblance is considered sufficiently close to permit calling the secretion a hornblende-soda andesite-basalt.

The hornblende-soda andesite-basalt and augite andesite-basalt of Bill Williams Mountain furnish an example of two rocks of similar chemical composition which have crystallized in divergent modes, as may be seen by comparing their composition given in columns 1 and 5 of the foregoing table. The presence of hornblende in one rock and of pyroxene and olivine in the other is sufficient to change the relative amounts of the salic and calfemic minerals by about 20 per cent.

Composition of the hornblende.—The composition of the hornblende used in calculating the mode of the secretion is as follows:

Composition of hornblende in secretion at Bill Williams Mountain and of average hornblende.

	1	2	3		1	2	3
SiO_2	42.1	44.0	47.49	K_2O	0.9	1.0	0.49
Al_2O_3	13.5	13.0	7.07	H_2O	....	.5	1.86
Fe_2O_3	7.7	6.0	4.88	TiO_2	2.4	.5	1.21
FeO	6.1	5.5	10.69	MnO	....	.5	.51
MgO	13.3	14.0	13.06				
CaO	12.0	12.5	11.92		99.8	99.5	99.93
Na_2O	1.8	2.0	.75				

1. Hornblende used in the mode of Bill Williams Mountain secretion (2384a).
2. Hornblende of average composition (analyses Nos. 100–119, Dana's Mineralogy, pp. 395–396).
3. Hornblende used in the mode of soda dacite of Bill Williams Mountain (2351).

The changes introduced into the hornblende of average composition in order to make it fit the mode of the secretion are slight. As compared with the hornblende of the lava which incloses the secretion, silica is lower, whereas alumina, alkalies, and titania are higher. These are characteristic differences between hornblendes of basic and acidic rocks[1] and they confirm the impression that the composition of the hornblende used in calculating the mode of the secretion does not greatly differ from the actual composition of that mineral.

Conclusion.—The mode of occurrence and the mineral composition of the inclusions in the lava at Bill Williams Mountain and the other localities in the San Franciscan field, make it most simple to consider them as basic differentiation products of the lava in which they are found. The inclusions at Bill Williams Mountain might possibly be considered as recrystallized fragments of the augite andesite-basalt of the preceding stage of eruption, as they resemble it closely in chemical composition. At San Francisco Mountain and Kendrick Peak, however, the lava which corresponds to the augite andesite-basalt of Bill Williams Mountain was erupted at a considerably later stage in the history of the volcanoes than that in which the inclusions occur, and at O'Leary Peak it is absent. To consider the inclusions, therefore, as derived from the augite andesites introduces complexities into the differentiation of the magma which are not indicated by the sequence of lavas found at any of the large cones. The field evidence shows that the inclusions were in a solid state at the time they were caught up and brought to the surface by their inclosing lava. From what depth they came is a matter of conjecture. The hyaline texture of the groundmass suggests that crystallization occurred in the upper part of the conduits of the volcanoes.

THE BASALTIC LAVAS.

The lavas of the basaltic group are in all respects typical basalts. In distinction to the lavas already described, which built up isolated and generally large cones, they were erupted from small cones and covered at a maximum over 2,000 square miles.

No. 22. AUGITE BASALT OF CEDAR RANCH MESA (AUVERGNOSE, III.5.4.4).

Occurrence.—The augite basalt of which the lava outcropping at the edge of the mesa above Cedar Ranch is taken as the type covers a very extensive area in the southwestern part of the Plateau country.

Megascopic characters.—The lava is typically medium to dark gray in color and has a compact and generally uniform cryptocrystalline texture. It commonly contains from 10 to 15 per cent of iridescent olivine phenocrysts, which are from 1 to 3 millimeters in diameter. Some of it contains amygdules of calcite, a feature that is noticeable in the region south of the pumping station on the Black Mesa. A very slight effervescence is produced by hydrochloric acid in the type lava from Cedar Ranch, indicating the presence of calcite, which is not megascopically observable.

Microscopic characters.—The lava is holocrystalline, except for the presence of 1 or 2 per cent of interstitial glassy base, and has a typical doleritic texture. It is in fact identical in character with the more recent basalt of the region represented by specimen 2169, from Ken-

[1] Iddings, J. P., Rock minerals, 1906, pp. 337–338.

drick Peak, except that it is commonly coarser grained. The minerals present are apatite, magnetite, olivine, plagioclase (Ab_3An_4), and augite. A small amount of infiltrated calcite is commonly present and also a completely altered mineral of unidentified character. The olivine is generally more or less changed to a dull opaque mass which preserves the crystalline form of the mineral and very little of it is entirely fresh. The other minerals, however, are perfectly fresh.

Chemical composition.—The analysis of the type specimen (1911) from Cedar Ranch Mesa gave the following results:

Chemical analyses of augite basalt of Cedar Ranch Mesa and related rocks.

	1		2	3	4	5
	Per cent.	Molecular ratio.				
SiO_2	47.70	0.797	49.73	47.41	48.0	54.28
Al_2O_3	15.30	.145	15.96	16.35	16.3	18.16
Fe_2O_3	5.93	.037	6.18 [a] 3.5	3.37	4.0	9.52
FeO	4.85	.067	5.05 [a] 7.5	7.72	7.6	....
MgO	7.31	.183	7.62	8.55	7.3	1.53
CaO	11.83	.211	9.85	10.45	9.9	2.08
Na_2O	2.46	.040	2.56	2.50	2.8	2.24 (Na_2O + K_2O)
K_2O	.61	.006	.64	.75	1.1	
H_2O+	.34	....	.35	.11	1.2	13.01 (H_2O+, H_2O-, CO_2)
H_2O-	.10	....	.10	.08	.2	
CO_2	1.87	.042	....	None.	....	
TiO_2	1.45	.018	1.51	1.54	1.4	....
P_2O_5	.29	.002	.31	.49	.3	....
SO_3	None.	....	....	None.	....	....
Cl	Trace.	....	....	Trace.	....	....
MnO	.46	.006	.50	.27	.2	....
SrO	.02	....	.02	Trace.	....	....
BaO	.09	.001	.09	.04	....	....
	100.61	....	100.47	99.94	100.3	100.82

[a] Corrected values for fresh rock.

1. Augite basalt, Cedar Ranch Mesa, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.95.
2. Same, with 4.25 per cent of infiltrated calcite removed.
3. Augite basalt, Kendrick Peak, San Franciscan volcanic field.
4. Type basalt.
5. Residual clay resulting from weathering of basalt of the San Franciscan field. F. N. Guild, analyst.

The lava is a typical basalt and differs only very slightly in composition from the basalt of Kendrick Peak and the type basalt. The altered condition of the olivine is expressed in the reversed values of the ferric and ferrous iron, and the high lime is due to the presence of infiltrated calcite. The calcite amounts to 4.25 per cent, composed of 2.38 per cent of lime and 1.87 per cent of carbon dioxide, and the composition of the lava with this removed is given in column 2. The necessity of removing not only the carbon dioxide but also the lime combined with it is indicated by the perfectly fresh condition of the augite and plagioclase.

Mineral composition.—The mode can not be satisfactorily calculated from the chemical composition on account of the altered condition of some of the dark minerals. However, as the lava is holocrystalline, it may be approximately obtained from a micrometric analysis. The results are as follows:

Mineral composition of augite basalt of Cedar Ranch Mesa.

	Composition by volume.			Composition by weight.	Average size of crystals (millimeter).
	1	2	Average.		
Interstitial base (=orthoclase)	1.9	0.9	1.4	1.2	....
Labradorite (Ab_3An_4)	50.7	54.5	52.6	47.1	0.08
Augite	23.1	20.8	22.0	24.1	.04
Olivine	11.7	11.7	11.7	13.2	.17
Magnetite	4.5	4.1	4.3	7.3	.04
Calcite	4.6	5.3	4.9	4.1	....
Unidentified	3.5	2.7	3.1	3.1	....
	100.0	100.1	100.0	99.9	.07

1 and 2. Composition from two sets of traverses at right angles.

It was necessary to make a special determination of the amount of olivine on account of the variable size and distribution of that mineral in the lava, and the value obtained is common to both sets of traverses. The agreement between the two sets of traverses is not very close, but the average values are not far from the true ones, as may be seen by comparison with the amounts of certain of the minerals obtained by calculation. The calculated amount of feldspar, for example, is about 51 per cent, as compared with a measured quantity of 48.3 per cent. Calculated calcite is 4.2 per cent, as against 4.1 per cent measured. Calculated magnetite, assuming the ferric oxide to be present in average amount, is 6.8 per cent, as compared with a measured quantity of 7.3 per cent. The micrometric analysis, therefore, may be accepted as a fair approximation of the correct mineral composition of the lava. The salic and calfemic minerals are very nearly equal in amount. The former consist almost entirely of plagioclase of the composition Ab_3An_4, whereas augite and olivine are the principal dark minerals.

No. 23. AUGITE BASALT OF KENDRICK PEAK (AUVERGNOSE, III.5.4.4).

Occurrence.—The augite basalt here described covers an area of some 1,200 square miles near the large volcanoes of the second general period of eruption in the San Franciscan volcanic field.

Megascopic characters.—The lava is medium to dark gray, less commonly bluish black. Its texture is compact and generally aphanitic, though locally microcrystalline. Porphyritic varieties which contain a small amount of feldspar and olivine phenocrysts averaging about 3 millimeters in length are common. The lava is, in fact, typically basaltic in appearance.

Microscopic characters.—The lava has a holocrystalline texture, as interstitial glassy material constitutes only 2 or 3 per cent of the rock. The texture is in general of the doleritic type, although very rarely the augite occurs in the form of large individuals poikilitically intergrown with small plagioclase crystals. The minerals present are apatite, magnetite, olivine, plagioclase (Ab_3An_4), and augite. The lava is a typical augite basalt containing about 10 per cent of olivine. In many specimens it is indistinguishable from the augite basalt of the first general period of eruption of the region. In the type specimens the lava of the third period has somewhat higher augite and lower olivine than that of the first. The differences, however, are probably no greater than occur in either rock mass alone.

Crystallinity of the lava.—The lava is invariably fine grained and generally the crystals are too small to be measured. The type specimen (2169), from the west slope of Kendrick Peak, however, is coarser than the average and it was possible with some labor to make a micrometric analysis of it. As the lava is holocrystalline, the analysis gives the mode, which is as follows:

Mode of augite basalt of Kendrick Peak.

	Composition by volume.			Composition by weight.	Average size of crystals (millimeters).
	1	2	Average.		
Labradorite (Ab_3An_4)	58.4	57.3	57.8	50.8	0.025
Augite	27.9	29.1	28.5	30.8	.015
Olivine	7.9	8.7	8.4	9.2	.10
Magnetite	5.8	5.0	5.4	9.1	.012
	100.0	100.1	100.1	99.9	.027

1 and 2. Composition from two sets of traverses at right angles. Distances traversed, 9.4 and 10.4 centimeters, respectively.

The lava consists of equal parts of salic and calfemic minerals. The salic constituent is entirely plagioclase of the composition Ab_3An_4; the calfemic constituents are two-thirds augite. As the lava is practically holocrystalline, an opportunity is presented to check the micrometric analysis with the calculated mode. The differences are: Feldspar, 1.5 per cent; augite, 0.6 per cent; ore, 2.5 per cent. The amounts of olivine can not be compared because the measured quantity is used in the calculated mode. The magnetite has been overmeasured by nearly 40 per cent. This is due to the dark color and very small size of the crystals, their average diameter being only 0.012 millimeter, or about half the thickness of the thin section. The error is a common one even when the crystals are much larger; it probably can not be eliminated when the crystals are small except by the use of a constant. The differences in the amounts of feldspar and augite, as determined by the two methods, are slight and would disappear if the micrometric values were corrected for the error in the magnetite. The amounts of these two minerals, which are light colored, have thus been correctly determined by measurement. The result is of interest because of the small size of the crystals; the average size of the feldspar is 0.025 millimeter, or about the thickness of the thin section, and the average size of the augite is only 0.015 millimeter. It may be stated, therefore, that the amount of feldspar and augite, and light-colored minerals in general, may be correctly determined by the Rosiwal method in basaltic lavas, when the average size of the crystals is no greater than the thickness of the thin section. The amount of magnetite, on the other hand, is always likely to be overestimated unless the average diameter of the crystals exceeds the thickness of the thin section. The error is probably more or less constant and could be eliminated by applying a correction to be determined by experiment.

Chemical composition.—The analysis of the fresh type specimen (2169) from the west slope of Kendrick Peak gave the following results:

Chemical analyses of augite basalt of Kendrick Peak and related rocks.

	1		2	3	4	5
	Per cent.	Molecular ratio.				
SiO_2	47.41	0.790	48.0	51.78	49.88	51.22
Al_2O_3	16.35	.160	16.3	12.79	18.55	14.06
Fe_2O_3	3.37	.021	4.0	3.59	2.06	4.32
FeO	7.72	.107	7.6	8.25	8.37	8.73
MgO	8.55	.214	7.3	7.63	5.77	4.42
CaO	10.45	.186	9.9	10.70	9.72	8.33
Na_2O	2.50	.040	2.8	2.14	2.59	2.55
K_2O	.75	.008	1.1	.39	.68	1.25
H_2O+	.11		1.2	.63	1.04	1.28
H_2O-	.08		.2			
CO_2	None.					
TiO_2	1.54	.019	1.4	1.41	1.19	2.42
P_2O_5	.49	.004	.3	.14	.16	.25
SO_3	None.					
Cl	Trace.					
MnO	.27	.004	.2	.44	.09	.16
SrO	Trace.					
BaO	.04					
	99.63		100.3	99.89	100.12	99.67

1. Augite basalt, Kendrick Peak, San Franciscan volcanic field, Arizona. H. H. Robinson, analyst. Specific gravity, 2.95.
2. Type basalt.
3. Diabase, West Rock, New Haven, Conn. G. W. Hawes, analyst. (Am. Jour. Sci., 3d ser., vol. 9, 1875, p. 185.)
4. Olivine diabase, Pigeon Point, Minn. W. F. Hillebrand, analyst. (Bull. U. S. Geol. Survey No. 228, 1904, p. 88.)
5. Diabase, Whin Sill, Cauldron Snout, Durham, England. (Rosenbusch, H., Elemente der Gesteinslehre, 1898, p. 323.)

The lava of Kendrick Peak is so similar in composition to the type rock that it may be considered a typical basalt. It is also much the same as the three diabases, which will be referred to when the composition of the augite of the basalt of Kendrick Peak is considered.

Mineral composition.—The mineral composition is calculated as follows:

Calculated mineral composition of augite basalt of Kendrick Peak.

	Percentage.	SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	MgO.	CaO.	Na_2O.	K_2O.	TiO_2.	P_2O_5.	MnO.
Percentage		47.41	16.35	3.37	7.72	8.55	10.45	2.50	0.75	1.54	0.49	0.27
Apatite	1.1						0.64				0.49	
Magnetite	4.4			3.04	1.37							
Ilmenite	2.2				1.01					1.20		
Olivine	9.2	3.66			1.46	4.08						
Orthoclase	4.1	2.65	.75						0.70			
Albite	19.0	13.05	3.71					2.25				
Anorthite	29.1	12.57	10.68				5.85					
Sum		31.93	15.14	3.04	3.84	4.08	6.47	2.25	.70	1.20	.49	
Remainder (=augite)	30.2	15.48	1.21	.33	3.88	4.47	3.96	.25	.05	.34		.27

All the phosphoric pentoxide goes into apatite. All the ferric iron, titania, and alkalies, except the small amounts in the augite, go into magnetite, ilmenite, orthoclase, and albite, carrying with them their proportionate amounts of the other oxides. The amount of olivine can not be determined from the chemical analysis because in common with the augite it contains ferrous iron and magnesia. The amount, therefore, has been taken from the micrometric analysis. The ratio of MgO : FeO is assumed as 5:1; the ferrous iron is at least greater than 12 per cent, as the olivine is optically negative. The amount of anorthite is governed by the composition of the plagioclase, determined in thin section as Ab_3An_4. The actual ratio of albite to anorthite in the table is 2:3. It is probable, however, that the potash is almost entirely in the plagioclase, as orthoclase is not seen in thin section. The average amount of potash in the albite-anorthite series, as determined from 49 analyses in Dana's Mineralogy, is 1 per cent (the maximum value being over 3 per cent), which is equivalent to 6 per cent of orthoclase. It is permissible, therefore, to add 3 per cent of the orthoclase in the table to albite, as there is nearly 50 per cent of plagioclase in the lava, and by so doing a ratio of albite to anorthite of 22:29, or practically 3:4, is obtained. There is then left 1.1 per cent of orthoclase, which is presumably represented by the small amount of glassy interstitial material present in the lava. The remaining portions of the oxides, left after the above calculations have been made, all go into augite. The mode of the lava is, then, as follows:

Modes of basalt of Kendrick Peak and of type basalt.

	1	2	3
Orthoclase	1.1	3.8	−2.7
Labradorite (Ab_6An_7)	....	52.0	....
Labradorite (Ab_3An_4)	51.2	....	−0.8
Augite	30.2	26.2	+4.0
Olivine	9.2	9.0	+0.2
Magnetite	6.6	7.2	−0.6
Apatite	1.1	.7	+0.4
Water	.2	1.4	....
	99.6	100.3	{ +4.6 −4.1

1, Mode of basalt of Kendrick Peak; 2, mode of type basalt; 3, departures of mode 1 from mode 2.

The basalt of Kendrick Peak has practically the same composition as the type basalt, although the plagioclase is slightly more basic. It is classified as an augite basalt.

Composition of the augite.—The correctness of the composition of the augite and its character may be seen by resolving it into its component molecules in the following manner:

Composition of augite from basalt of Kendrick Peak.

Oxide.	Percentage by weight.	Molecular ratios.	$(Na, K) Al (SiO_3)_2$.	$(Mg, Fe) (Al, Fe)_2 SiO_6$.	$(Fe, Mn) SiO_3$.	$MgSiO_3$.	$CaSiO_3$.	SiO_2.
SiO_2	15.48	0.258	20	9	55	106	71	1
Al_2O_3	1.21	.012	5	7	....	....	....	....
Fe_2O_3	.33	.002	....	2	....	....	....	....
FeO	3.88	.054	....	3	51	....	....	....
MgO	4.47	.112	....	6	....	106	....	....
CaO	3.96	.071	....	....	....	....	71	....
Na_2O	.25	.004	4	....	....	....	....	....
K_2O	.05	.001	1	....	....	....	....	....
TiO_2	.34	.004	....	....	....	....	....	....
MnO	.27	.004	....	....	4	....	....	....

It is evident that the augite does not have the composition of the pure mineral but is mixed with hypersthene. It is equally evident that the composition of the mineral as calculated from the chemical composition is correct, for it may be resolved into the several components which theoretically make up augite and hypersthene. If the mixture is resolved into these two minerals, the MgO and FeO in the augite being given a ratio of 2.5: 1, or about the average for that mineral, it is found to consist of about 20 per cent of augite and 10 per cent of hypersthene. It would be more proper, therefore, to call it a hypersthenic augite, or an augitic pyroxene, rather than simply an augite.

The composition may be more clearly seen by calculating it on the basis of 100 per cent. The result is given below, with the analyzed pyroxenes from the three diabases whose analyses have been quoted in the preceding section.

Chemical analyses of augite, pyroxene, and diallage from various sources.

	1	2	3	4
SiO_2	51.2	50.71	48.34	49.03
Al_2O_3	4.0	3.55	2.90	5.46
Fe_2O_3	1.1	....	4.68	....
FeO	12.8	15.30	14.15	15.57
MgO	14.8	13.61	11.34	11.66
CaO	13.1	13.55	15.10	15.34
Na_2O	.8	1.48 (Na₂O + K₂O)	....	1.24
K_2O	.2			
TiO_2	1.1	....	1.98	....
MnO	.9	.81	....	.22
H_2O	....	1.17	....	.81
	100.0	100.18	98.49	99.33

1. Calculated composition of hypersthenic augite from basalt of Kendrick Peak.
2. Pyroxene from diabase, West Rock, Conn. G. W. Hawes, analyst. (Am. Jour. Sci., 3d ser., vol. 9, 1875, p. 185.)
3. Diallage from olivine diabase, Pigeon Point, Minn. R. B. Riggs, analyst. (Bull. U. S. Geol. Survey No. 228, 1904, p. 88.)
4. Augite from diabase, Whin Sill, Cauldron Snout, Durham, England. (Rosenbusch, H., Elemente der Gesteinslehre, 1898, p. 321.)

The analyses of the minerals show the same degree of resemblance as the analyses of the rocks themselves, and certain differences they exhibit depend very closely on differences in the composition of the rocks, as may be seen in the following table:

Comparative composition of rock and pyroxene of basalt of Kendrick Peak and of diabases from different localities.

	Kendrick Peak.	West Rock.	Pigeon Point.	Whin Sill.
Ferrous iron:				
In the rocks	7.72	8.25	8.37	8.73
In the pyroxene	12.8	15.3	14.15	15.57
Magnesia:				
In the rocks	8.55	7.63	5.77	4.42
In the pyroxene	14.8	13.6	11.34	11.66
Lime:				
In the rocks	10.45	10.70	9.72	8.33
In the pyroxene	13.1	13.55	15.10	15.34

The ferrous iron and magnesia in the pyroxene vary almost directly as do the same oxides in the rocks. Olivine is absent in the diabases of West Rock and Whin Sill, but present to the extent of about 10 per cent in the basalt of Kendrick Peak and the diabase of Pigeon Point; its presence corresponds with a lower silica content in these two rocks. As the olivine is an earlier crystallization product than the pyroxene and, unless excessively rich in ferrous iron, contains magnesia and ferrous iron in a different ratio from that of the pyroxene, it would be expected to exercise some influence on the composition of that mineral, and the same would presumably be true of magnetite and ilmenite. This influence, if it exists, is not easily detected, although ferrous iron and magnesia are relatively lower in the olivine rocks than in those which contain only pyroxene. The pyroxenes with the highest lime are clearly associated with the rocks containing the lowest lime, and the relation is therefore an inverse one. The pyroxene in the rocks with lower lime thus contains a greater proportion of the diopside molecule, as compared with the orthorhombic pyroxenes, than does the pyroxene in the rocks with higher lime. The interesting question as to the relation between the pyroxene and plagioclase, both lime-bearing, can not be touched on for want of proper data.

CHAPTER VI.

PETROLOGY.

OUTLINE OF DISCUSSION.

The subjects considered in this chapter fall into three groups. The first group includes the calculation and discussion of the average lavas of (*a*) the three general periods of eruption, (*b*) the composite cones, (*c*) the entire region, and (*d*) the main rock types. Of particular interest is the fact that the average lavas of the composite cones have practically the same composition as the average lava of the second period of eruption, to which they belong. Although the exact significance of this fact is not certain, it is suggestive of the original homogeneity of the parent magma.

The second group of subjects includes the differentiation of the lavas in time and space, and related topics. It is concluded that differentiation occurred in a deep-seated zone and that the original composition of the magma was probably basaltic.

The third group embraces the discussion of the serial relationship of the lavas as expressed by their (*a*) chemical composition, (*b*) mineral composition on the basis of holocrystallinity, (*c*) actual crystallinity, or texture, (*d*) specific gravity, and (*e*) other characters.[1] By plotting the bases with reference to silica it is found that they fall into three groups according to their relative strength. It is shown that in the lavas of intermediate composition there is a slight excess of alumina over lime and alkalies, which forms a solid solution with the alkali feldspars instead of crystallizing as corundum. It is found that the calculated specific gravities of the lavas, considered as holocrystalline rocks, are practically a linear function of silica, or of mineral composition. It is shown that the actual crystallinity of the lavas, with one significant exception, is also a linear function of the mineral composition. Of particular interest are the serial mineral characters of the lavas on the basis of holocrystallinity. It is determined that the minerals fall into two groups which reach saturation (maximum) values at opposite ends of the series. Definite limits are thus set to the San Franciscan sequence of lavas and the composition of the end members may be closely calculated. It is concluded that the lavas may be considered as representing all possible members of the igneous series which could form under the magmatic conditions existing in the San Franciscan region. The possible bearing of this feature on the distribution of igneous rocks in general with respect to their composition is briefly touched upon.

The final conclusion is reached from the study of the various serial characters that the lavas of the San Franciscan region form a genetically related series of pronounced continuity and are the differentiation products of an originally homogeneous magma. It is also concluded that the lavas were derived from the original magma, or originated according to the laws of chemical solution.

COMPOSITION OF THE AVERAGE LAVAS OF THE THREE GENERAL PERIODS OF ERUPTION.

In this section is given the composition of the average lavas of the three general periods of eruption of the region. The composition of the average lavas of the composite cones is also given in connection with the average lava of the second period, to which they belong. Conditions are favorable for the determination of the volumes of the lavas in this region, and these

[1] Since this chapter was originally written two important books have appeared which deal in a general way with the problems here treated in a special manner. They are "Igneous rocks," by J. P. Iddings (1909), and "The natural history of igneous rocks," by Alfred Harker (1909). They would otherwise naturally be referred to, as the treatment of some of the problems and the results reached are similar in character to those here presented, a coincidence evidently due to working with a common point of view.

have been either calculated or estimated for all the important rock masses. It has thus been possible to give each lava mass its proper weight, which has been done by using volumes. It would be more correct of course to weight the lavas by mass. However, the errors caused by the use of volumes are very slight and in view of probable errors in the several factors that enter into the final result it would be an overrefinement to weight by mass.

FIRST PERIOD.

Only one lava was erupted during the first period. It is a typical basalt, and a study of numerous thin sections of specimens from all parts of the field shows that it has a decidedly uniform mineral composition. Consequently it is probable that it has an equally uniform chemical composition. The volume of the lava flows and cones which are included in the San Franciscan volcanic field is estimated at 30 cubic miles. The chemical composition of the lava, corrected for 4.3 per cent of infiltrated calcite and with ferric and ferrous iron in amounts found in fresh rock, is as follows:

Chemical composition of lava of first general period of eruption.

SiO_2	49.7	H_2O+	0.4
Al_2O_3	16.0	H_2O-	.1
Fe_2O_3	3.5	TiO_2	1.5
FeO	7.5	P_2O_5	.3
MgO	7.6	MnO	.5
CaO	9.8	BaO	.1
Na_2O	2.6		
K_2O	.6		[1] 100.2

The similarity of the lava throughout the region is notable and is exhibited by the corresponding basalts of the surrounding Plateau country. In fact, the uniformity of basaltic eruptions over large areas is common and is further illustrated in this country by the Triassic basalts and diabases of the New England and Atlantic States and by the lavas of the Columbia River and Snake River lava plateaus. It seems reasonable to conclude, in view of the highly uniform character of these lavas over such large areas and the fact that their eruption extended through a considerable interval of geologic time, that they closely represent their parent magma. This conclusion applies to the basalt of the first period of eruption and also to that of the third period in the San Franciscan field, as both are throughout of very uniform mineral composition.

SECOND PERIOD.

The lavas of the second period embrace a number of different varieties, ranging from andesites to rhyolites, which generally built up large isolated cones as described in Chapter III (pp. 40–87). Five of the cones are composed of two or more different lavas, and for each of these the average composition of the lava has been calculated. The average lava of the entire period is the average of all the different lava masses weighted by volume. It may be conveniently obtained by considering the composition of the lavas as they occur at the several cones in the following order:

SAN FRANCISCO MOUNTAIN.

The average lava of this volcano is made up of the five lavas which were erupted from the main and lateral vents of the cone, and in addition the three closely associated masses of Marble, Sugarloaf, and the Dry Lake hills. The lava of the Dry Lake Hills, which has not been analyzed is included in the hypersthene-soda dacite of San Francisco Mountain, as it is very closely related to it. The measured volume of the latite is 21 cubic miles. From the exposures on the inner slope of San Francisco Peak it is estimated that two-thirds of this volume is in the form of fragmental material. An allowance of 20 per cent for the porosity of this portion

[1] Throughout this chapter the percentage values of the oxides of the chemical analyses and of the minerals of the modes are given only to the nearest tenth place of decimals. The hundredth place of decimals would possess no significance, as, indeed, it possesses none in a number of analytical determinations. It would be most desirable to give the probable error of the determinations, but this is hardly possible.

places the volume of compact lava at 18.2 cubic miles. The individual lavas and the volumes by which they are weighted are:

No. 1.[1] Biotite rhyolite; volume, 0.2.
No. 2. Biotite-soda granite porphyry; volume, 0.7.
No. 4. Riebeckite-soda rhyolite; volume, 0.5.
No. 8. Biotite-hornblende dacite; volume, 0.5.
No. 9. Hypersthene-soda dacite; volume, 13.5.
No. 17. Pyroxene-hornblende latite; volume, 18.2.
No. 18. Augite andesite; volume, 3.0.

The composition of the average lava is as follows:

Chemical composition of average lava of San Francisco Mountain.

SiO_2	62.0	H_2O+	0.3
Al_2O_3	16.7	H_2O-	.4
Fe_2O_3	2.8	TiO_2	1.0
FeO	3.1	P_2O_5	.3
MgO	1.6	MnO	.1
CaO	3.6	BaO	.1
Na_2O	4.7		
K_2O	3.1		99.8

Specific gravity, 2.61.

The hypersthene-soda dacite and pyroxene-hornblende latite, on account of their preponderant mass, fix the character of the average lava. In fact, the result would be little changed if the rhyolites and the andesite were omitted from the calculation, for the average composition of those two lavas happens to be very nearly the same as the average of all the lavas. The average lava is, therefore, intermediate in composition between a soda dacite and a latite. It may be classified as a basic soda dacite or as a quartz latite; in either case it is a lava with a trachytic cast.

KENDRICK PEAK.

The average lava of Kendrick Peak is composed of the four lavas which were erupted at this volcano. They are as follows:

No. 6. Biotite dacite; volume, 5.3.
No. 13. Pyroxene dacite; volume, 0.4.
No. 14. Hypersthene dacite; volume, 0.6.
No. 19. Augite andesite; volume, 0.1.

The average composition of the lava is as follows:

Chemical composition of average lava of Kendrick Mountain.

SiO_2	67.4	H_2O+	0.7
Al_2O_3	15.5	H_2O-	.2
Fe_2O_3	2.7	TiO_2	.4
FeO	2.0	P_2O_5	.2
MgO	1.1	MnO	undet.
CaO	2.2	BaO	undet.
Na_2O	4.3		
K_2O	3.6		100.2

Specific gravity, 2.51.

The biotite dacite, on account of its much greater weight, exercises the controlling influence on the composition of the average lava, which may be considered a rather acidic dacite.

[1] These numbers correspond to those under which each lava is described in Chapter V. They are also the same as those affixed to the lavas in the table of analyses, etc., given in this chapter.

BILL WILLIAMS MOUNTAIN.

The average lava of Bill Williams Mountain is made up as follows:

No. 12. Hornblende-soda dacite; volume, 2.2.
No. 20. Augite andesite-basalt; volume, 0.7.

The composition of the lava is as follows:

Chemical composition of average lava of Bill Williams Mountain.

SiO_2	62.4	H_2O+	0.6
Al_2O_3	16.6	H_2O-	.2
Fe_2O_3	2.7	TiO_2	.9
FeO	2.8	P_2O_5	.2
MgO	2.3	MnO	Undet.
CaO	4.7		
Na_2O	4.4		100.5
K_2O	2.6		

Specific gravity, 2.57.

The measured volume of andesite-basalt, 0.8 cubic mile, is reduced to 0.7 to allow for the breccia that is present. The lava may be considered a rather basic soda dacite, to which the high lime and low potash give an andesitic cast.

O'LEARY PEAK.

The average lava of O'Leary Peak is made up of the following lavas:

No. 7. Biotite dacite; volume, 0.9.
No. 15. Hornblende dacite; volume, 1.2.

The average composition is as follows:

Chemical composition of average lava of O'Leary Peak.

SiO_2	64.3	H_2O+	0.6
Al_2O_3	16.4	H_2O-	.1
Fe_2O_3	2.7	TiO_2	.7
FeO	2.8	P_2O_5	.2
MgO	1.4	MnO	Undet.
CaO	3.0		
Na_2O	4.6		100.1
K_2O	3.3		

Specific gravity, 2.54.

The average lava may be considered a slightly sodic dacite with a trachytic cast.

MORMON MOUNTAIN.

The average lava of Mormon Mountain is composed of the following two lavas:

No. 11. Hornblende-soda dacite; volume, 0.5.
No. 16. Pyroxene latite; volume, 1.5.

The composition is as follows:

Chemical composition of average lava of Mormon Mountain.

SiO_2	62.9	H_2O+	0.8
Al_2O_3	17.1	H_2O-	.1
Fe_2O_3	2.0	TiO_2	.6
FeO	2.5	P_2O_5	.2
MgO	2.2	MnO	Undet.
CaO	4.4		
Na_2O	5.0		100.1
K_2O	2.3		

Specific gravity, 2.59.

The lava may be considered an acidic latite to which the low potash gives an andesitic cast.

OTHER LOCALITIES.

The rest of the lava masses which make up the average lava of the second period of eruption are each composed of a single lava. They are as follows:

No. 3. Biotite-soda rhyolite, Sitgreaves Peak; volume, 3 cubic miles.
No. 10. Hypersthene-hornblende-soda dacite, Elden Mountain; volume, 1.8 cubic miles.
Hornblende latite, Observatory Mesa; volume, 0.5 cubic mile.
Biotite-soda rhyolite, Slate Mountain; volume, 0.5 cubic mile.

The composition of the lavas of Sitgreaves Peak and Elden Mountain is given in the preceding chapter. The lavas of Slate Mountain and Observatory Mesa have not been analyzed. Mineralogically, however, they are very similar to the soda rhyolite of Marble Hill and the latite of San Francisco Mountain, and on account of their small mass no especial error can result from assuming that they have similar chemical compositions.

AVERAGE LAVA OF SECOND PERIOD.

The average lava of the second period is composed of the several lava masses enumerated in the preceding paragraphs, weighted according to their volume. As these masses constitute probably 98 per cent of all the lava erupted during this period the result is thoroughly representative. The several lava masses are:

Lava masses of second general period of eruption.

	Volume (weight), cubic miles.		Volume (weight), cubic miles.
San Francisco Mountain	36.6	Elden Mountain	1.8
Kendrick Peak	6.4	Observatory Mesa	.5
Bill Williams Mountain	2.9	Slate Mountain	.5
O'Leary Peak	2.1		
Mormon Mountain	2.0		55.8
Sitgreaves Peak	3.0		

The composition of the average lava as thus made up is as follows:

Chemical composition of average lava of second general period of eruption.

SiO_2	63.8	H_2O+	0.4
Al_2O_3	16.3	H_2O-	.3
Fe_2O_3	2.6	TiO_2	.8
FeO	2.8	P_2O_5	.3
MgO	1.5	MnO	.1
CaO	3.3	BaO	.1
Na_2O	4.7		
K_2O	3.2		100.2

Specific gravity, 2.60.

The lavas of San Francisco Mountain exercise a predominating influence, as they constitute about two-thirds of the total volume of lavas that enter into the average. It may be noted that the rhyolites of Kendrick and Sitgreaves peaks and the dacites, latite, and andesite of San Francisco Mountain form 78 per cent of the total volume of lavas. The proportion in which the different types enter into the average may be stated as follows:

Proportion of types contained in the average lava of second general period of eruption.

Rhyolite	11.1
Dacite	20.7
Latite	20.2
Andesite	3.8
	55.8

Or, by resolving the dacite and latite into their component parts and reducing the sum to 100 the result is as follows:

Percentages of rhyolite, andesite, and trachyte in average lava of second general period of eruption.

Rhyolite	38.5
Andesite	43.5
Trachyte	18.0
	100.0

This method of statement brings out the fact that the average lava of the second period is a dacite with a well-marked trachytic cast. That is to say, it is a soda dacite in which the ratio of potash to soda is 1:2.2, as compared with 1:1.5 in the type dacite.

THIRD PERIOD.

The only lava erupted during the third period was a typical basalt. A study of the thin sections of widely distributed specimens shows that it has a uniform mineral composition and on this basis it is assumed that the chemical composition is equally constant. As the lava was erupted without change in composition through a considerable interval of geologic time the broader inference appears reasonable that, like the basalt of the first period of eruption, it fairly represents the composition of its parent magma. The volume of lava is estimated at 20 cubic miles. The composition is as follows:

Chemical composition of recent basalt of San Franciscan volcanic field.

SiO_2	47.4	H_2O+	0.1
Al_2O_3	16.4	H_2O-	.1
Fe_2O_3	3.4	TiO_2	1.5
FeO	7.7	P_2O_5	.5
MgO	8.6	MnO	.3
CaO	10.4		
Na_2O	2.5		99.7
K_2O	.8		

Specific gravity, 2.95.

AVERAGE LAVA OF THE SAN FRANCISCAN VOLCANIC FIELD.

METHOD OF DETERMINATION.

The average lava of the region is composed of the lavas of the three general periods of eruption, weighted by volume. They are as follows:

Lavas of the three general periods of eruption, weighted by volume.

	Cubic miles.
First period:	
Basalt	30
Second period:	
Rhyolite	11.1
Dacite	20.7
Latite	20.2
Andesite	3.8
Third period:	
Basalt	20
	105.8

If the intermediate types are resolved into their component parts and the sum of all reduced to 100, this average lava has the following composition, as expressed in percentages of the four main rock types: Trachyte, 9.5; rhyolite, 20.5; andesite, 23.0; basalt, 47.0; total, 100. The basalt exercises a predominant influence on the composition of the average, as its weight is nearly equal to that of the other three types combined. Evidently the lava is of medium composition, as the andesite and basalt types form 70 per cent of the total.

CHEMICAL COMPOSITION.

The chemical composition of the average lava of the San Franciscan volcanic field is as follows:

Chemical composition of average lava of San Franciscan volcanic field and related rocks.

	1	2	3	4
SiO_2	56.7	57.2	56.5	57.8
Al_2O_3	16.3	16.7	17.2	15.7
Fe_2O_3	3.0	3.7	3.2	3.3
FeO	5.1	4.1	5.3	3.8
MgO	4.6	3.9	3.2	3.8
CaO	6.5	6.4	6.0	5.2
Na_2O	3.7	3.5	4.1	3.9
K_2O	2.0	2.3	2.1	3.1
H_2O+	.3	1.1	.1	1.4
H_2O-	.2	.2	.1	.4
TiO_2	1.1	.7	1.5	1.0
P_2O_5	.3	.2	.3	.4
MnO	.2	.2	.1	.2
BaO	.1	....	.1	....
	100.1	100.2	99.8	100.0

1. Average lava of the San Franciscan volcanic field. Specific gravity, 2.76.
2. Type andesite.
3. Average augite andesite of second period of eruption, San Franciscan volcanic field.
4. Average rock of the earth's crust. (Washington, H. S., Prof. Paper U. S. Geol. Survey No. 14, 1903, p. 108.)

In chemical composition the average lava of the region is clearly an andesite little different from the type andesite. It is equally similar to the average augite andesite of the second period of eruption, which was erupted in the smallest volume of all the main types. It approaches most closely, however, to the augite andesite of Kendrick Peak, and this lava has an estimated volume equal to but one one-thousandth of the total volume of erupted lava. The characteristic feature of an excess of soda over potash, which is seen in the lavas of the second period, is somewhat masked in the average lava of the region on account of the dominating weight of the basalt. It persists, however, to a slight extent, as the ratio of potash to soda is 1: 2.9 in the average lava, as compared with 1: 2.3 in the type andesite.

The chemical composition of the average lava of the region also bears a notable resemblance to that of the average igneous rock of the earth's crust, the differences being slightly higher ferrous iron, magnesia, and lime and lower potash. Both rocks classify strictly as andose in the quantitative system, although the average rock of the earth's crust may be considered as intermediate between dacose, akerose, tonalose, and andose. It is an interesting fact that the relative volumes of the different lavas in the San Franciscan region are such as produce an average composition so similar to that of the average igneous rock of the earth's crust.

MINERAL COMPOSITION.

The normal mineral composition of the average lava of the region will evidently be very similar to that of the andesites of the second period of eruption. It is as follows:

Normal mineral composition of the average lava of the San Franciscan region and of type andesite.

	1	2	
Quartz	8.4	9.6	− 1.2
Orthoclase [a]	11.7	13.3	− 1.6
Albite	16.1	8.5	+ 7.6
Andesine (Ab_7An_9)	35.0	....	− 6.6
Andesine (Ab_1An_1)	....	41.6	....
Pyroxene [a]	17.5	19.0	} + 2.6
Olivine [a]	5.0	....	
Magnetite	5.1	6.3	
Apatite	.7	.4	
Water	.4	1.3	
	99.9	100.0	{ +10.2 − 9.4

[a] Orthoclase contains 0.35 per cent of hyalophane. Pyroxene consists of 14 per cent of augite of average composition and 3.5 per cent of hypersthene in which FeO : MgO :: 1 : 2.2. Olivine : FeO : MgO :: 1 : 3. These figures used in mode of average lava of the region.

1, Mode of average lava of San Franciscan volcanic field; 2, mode of type andesite; 3, departures of mode 1 from mode 2.

The mode is calculated in the same manner as the andesite of San Francisco Mountain and the plagioclase is given the same composition. The average lava is decidedly salic in character, as the feldspars and quartz form nearly three-quarters of the mode. On the other hand, andesine (Ab_7An_9) and calfemic minerals constitute nearly two-thirds of the total. As compared with the type andesite, albite is high and andesine is low, which is largely due to the more acidic composition of the plagioclase. The mode is that of a normal andesite.

HOMOGENEITY OF THE AVERAGE LAVAS OF THE COMPOSITE CONES.

The calculation of the composition of the average lavas of the five composite cones of the region brings out the interesting and, it is believed, significant fact that they are all very similar both to one another and to the average lava of the entire second period of eruption. This is seen in the following table:

Chemical composition of average lavas of the composite cones and average lava of second general period.

	1	2	3	4	5	6
SiO_2	63.8	62.0	67.4	64.3	62.4	62.9
Al_2O_3	16.3	16.7	15.5	16.4	16.6	17.1
Fe_2O_3	2.6	2.8	2.7	2.7	2.7	2.0
FeO	2.8	3.1	2.0	2.8	2.8	2.5
MgO	1.5	1.6	1.1	1.4	2.3	2.2
CaO	3.3	3.6	2.2	3.0	4.7	4.4
Na_2O	4.7	4.7	4.3	4.6	4.4	5.0
K_2O	3.2	3.1	3.6	3.3	2.6	2.3
H_2O+	.4	.3	.7	.6	.6	.8
H_2O-	.3	.4	.2	.1	.2	.1
TiO_2	.8	1.0	.4	.7	.9	.6
P_2O_5	.3	.3	.2	.2	.2	.2
MnO	.1	.1	Undet.	Undet.	.1	Undet.
BaO	.1	.1	Undet.	Undet.	Undet.	Undet.
	100.2	99.8	100.2	100.1	100.5	100.1
Specific gravity	2.60	2.61	2.51	2.54	2.57	2.59

1, Average lava of the second period of eruption; 2, of San Francisco Mountain; 3, of Kendrick Peak; 4, of O'Leary Peak: 5, of Bill Williams Mountain; 6, of Mormon Mountain.

An inspection of the analyses shows that they are very similar, and, according to present standards, would probably be considered identical. Of the 45 values of the nine principal oxides in the average lavas of the five composite cones, 65 per cent depart less than 0.5 per cent from the corresponding values in the average lava of the second period of eruption, and 87 per cent depart less than 1 per cent. Of the six values that depart 1 per cent or more, three are found in silica and three in lime. The magnesia and lime are higher and potash lower in the lavas of Bill Williams and Mormon Mountains than in the average lava of the second period of eruption, and this represents a phase of the regional differentiation of the lavas that will be considered later. The silica and alumina naturally show the smallest proportional departure, whereas magnesia and titania show the largest. Among the other oxides soda is very constant in amount. The differences between the six analyses are certainly no greater than might well be expected to occur in a single lava mass of rather small volume, yet the distance between Kendrick Peak and Mormon Mountain is 34 miles, that between Bill Williams Mountain and O'Leary Peak is 41 miles, and the area of the inclosing polygon is about 500 square miles.

In view of the similarity of these average lavas and the bearing it may have as evidence of the original homogeneity of the magma, it seems advisable to examine the results in order to determine whether they represent actual conditions or are due to chance.

All the chemical analyses were made on rock fragments which were but the merest fraction of the total mass of lava. It is obvious, therefore, that unless the lava masses were of very uniform composition the analyses would not be thoroughly representative. The evidence, although indirect, suggests such a uniformity. The selection of the type specimen for analysis was made only after the microscopic examination of thin sections (between 30 and 40 for the hypersthene-soda dacite of San Francisco Mountain, for example) from various parts of each lava mass. The aim was to secure a specimen that best represented, both mineralogically and texturally, the average of all sections. This method was deemed appropriate because the study of the thin sections showed that the lava masses were fairly uniform in character, a feature which was interpreted as indicating an equal constancy in chemical composition. Some idea on this point may be gained by comparing analyses 4 and 5 in the table on page 178, which represent the extrusive and intrusive phases of the same rock mass, and also analyses 8, 9, and 10 of similar lavas from different masses. With these last may be included the analysis of hypersthene andesite given in column 3 of the table at the top of page 125.

In regard to the volumes by which the lavas are weighted, those of San Francisco Mountain, Kendrick Peak, and Bill Williams Mountain are the result of field work of some detail and are reasonably correct. The volumes of the lavas of O'Leary Peak and Mormon Mountain are merely estimates. It may be noted, however, that the two lavas at each of these cones are rather similar in composition, and consequently their relative volumes may be considerably in error without materially modifying the final result. On the whole, therefore, it is believed that the compositions of the average lavas of the composite cones are fairly representative.

It seems probable that the homogeneity of the average lavas of the composite cones and their resemblance to the average lava of the second period is not a matter of chance, because (*a*) the tendency toward constancy of composition is exhibited by the average lavas of all the composite cones; (*b*) the individual lavas of each cone differ more or less in composition from those of the other cones; (*c*) the number of different lavas is not the same at all the cones; and (*d*) the volume of lava at different cones shows a wide variation. The last three points may be illustrated by the following table:

Character and volume (in cubic miles) of lavas of composite cones and of average lava of second period.

	1	2	3	4	5	6
Soda rhyolite	4.9	1.4				
Biotite dacite	5.3		5.3			
Soda dacite	19.4	14.0		0.9	2.2	0.5
Dacite	2.2		1.0	1.2		
Latite	20.2	18.2				1.5
Andesite	3.1	3.0	.1			
Andesite-basalt	.7				.7	
Total volume	55.8	36.6	6.4	2.1	2.9	2.0

1, Average lava of second period of eruption; 2, of San Francisco Mountain; 3, of Kendrick Peak; 4, of O'Leary Peak; 5, of Bill Williams Mountain; 6, of Mormon Mountain.

It appears most probable that the factors would not, purely as a matter of chance, combine so as to indicate homogeneity of composition in the average lavas of all the composite cones and the entire second period of eruption. Consequently it is supposed that the results express actual conditions.

It may be said, therefore, that the average lavas of the composite cones, those formed of two or more different lavas, of the San Franciscan volcanic field are practically homogeneous and are identical with the average lava of the entire second period of eruption to which they belong. Whether this feature of eruptive phenomena is to be found in other regions is not known. The definiteness of the phenomenon in the San Franciscan region, however, leads to the expectation that it should also be true of many other volcanic fields.

AVERAGE COMPOSITION OF THE MAIN ROCK TYPES.

It is possible to calculate, in addition to the average lavas of the three general periods of eruption and of the entire region, the average composition of the principal rock types. These embrace the following varieties:

Rhyolite, second period of eruption.
Dacite, second period of eruption.
Latite, second period of eruption.
Andesite, second period of eruption.
Basalt, first and third periods of eruption.

RHYOLITE.

The rhyolite type is composed of lavas found at San Francisco Mountain, Kendrick Peak, O'Leary Peak, Sitgreaves Peak, Sugarloaf Hill, Marble Hill, and Slate Mountain, as usual weighted according to volume. These lavas are grouped together on the basis of their common textural and mineralogic characteristics. They all possess typical rhyolitic textures and belong to the second period of eruption, although their eruption was not strictly contemporaneous. The composition of the average lava is as follows:

Chemical composition of average rhyolite of second period of eruption.

SiO_2	71.0	H_2O+	0.5
Al_2O_3	14.5	H_2O-	.1
Fe_2O_3	1.8	TiO_2	.2
FeO	1.5	P_2O_5	.1
MgO	.5	MnO	Trace.
CaO	1.1		
Na_2O	4.9		100.1
K_2O	3.9	Specific gravity, 2.44.	

This average lava is composed predominantly of soda rhyolites and biotite dacite. It has the composition, therefore, of a slightly basic soda rhyolite.

DACITE.

The average dacite is composed of lavas which occur at San Francisco Mountain, Kendrick Peak, O'Leary Peak, Bill Williams, Mormon, and Elden Mountains, and the Dry Lake Hills. These lavas are all closely related on textural and mineralogic grounds, but as the result of regional differentiation show some divergence in chemical composition. The composition of the lava is as follows:

Chemical composition of average dacite of second period of eruption.

SiO_2	64.7	H_2O+	0.3
Al_2O_3	16.6	H_2O-	.1
Fe_2O_3	2.5	TiO_2	.8
FeO	2.4	P_2O_5	.2
MgO	1.2	MnO	.1
CaO	3.2		
Na_2O	4.8		100.2
K_2O	3.3	Specific gravity, 2.62.	

Soda dacites comprise 90 per cent, and the lavas of San Francisco and Elden Mountains and the Dry Lake Hills form 70 per cent of this type. It is therefore a soda dacite and has practically the same composition as the average lava of the second general period of eruption.

LATITE.

The average latite is made up of lavas found at San Francisco and Mormon Mountains. As the volume of the lava of San Francisco Mountain is over ten times that of Mormon Mountain, the composition is practically that of the pyroxene-hornblende latite of San Francisco Mountain. The composition is as follows:

Chemical composition of average latite of second period of eruption.

SiO_2	59.9	H_2O-	0.6
Al_2O_3	17.1	TiO_2	1.0
Fe_2O_3	2.9	P_2O_5	.3
FeO	3.5	MnO	.1
MgO	2.2	BaO	.1
CaO	4.1		
Na_2O	4.6		99.7
K_2O	2.9		
H_2O+	.4	Specific gravity, 2.68.	

ANDESITE.

The average andesite is composed of lavas which occur at San Francisco Mountain, Kendrick Peak, and Bill Williams Mountain. The lava of Bill Williams Mountain classifies as an andesite-basalt, but is related to the andesites of the other two cones on textural and mineralogic grounds. The composition is as follows:

Chemical composition of average andesite of second period of eruption.

SiO_2	56.5	H_2O-	0.1
Al_2O_3	17.2	TiO_2	1.5
Fe_2O_3	3.2	P_2O_5	.3
FeO	5.3	MnO	.1
MgO	3.2	BaO	.1
CaO	6.0		
Na_2O	4.1		99.8
K_2O	2.1		
H_2O+	.1	Specific gravity, 2.76.	

The andesite of San Francisco Mountain constitutes 80 per cent of this lava, and thus strongly stamps its character on it.

BASALT.

The average basalt is composed of the basalts of the first and third general periods of eruption, both typical basalts of very similar composition. The composition is as follows:

Chemical composition of average basalt of first and third periods of eruption.

SiO_2	48.8	H_2O-	0.1
Al_2O_3	16.1	TiO_2	1.5
Fe_2O_3	3.4	P_2O_5	.4
FeO	7.6	MnO	.4
MgO	8.0	BaO	.1
CaO	10.1		
Na_2O	2.5		99.9
K_2O	.7		
H_2O+	.2	Specific gravity, 2.95.	

DIFFERENTIATION OF THE LAVAS IN SPACE.

PERIOD OF OCCURRENCE.

The lavas of the first and third general periods of eruption experienced no differentiation in space. Each period is represented by a single lava—a typical basalt—which, so far as the thin sections show, has everywhere the same composition. Conditions during the second period of eruption, however, were to some extent reversed, and a slight but appreciable amount of differentiation took place, which is expressed by minor changes in the chemical composition of the lavas. It is not easily detected in the mineral composition on account of the hypocrystallinity of the lavas, and, except in a few lavas, it fails to be expressed texturally.

To illustrate the regional differentiation of the lavas of the second period, the chemical analyses of each group of related rocks are arranged with respect to the relative distances of the cones at which the lavas occur from San Francisco Mountain. The preponderant volume of lava in San Francisco Mountain marks this volcano as the eruptive center of the region, and, as may be seen from figure 25, the other cones of the second period are distinctly, though irregularly, grouped about it. It is also probable that this cone should be considered as marking the magmatic center of the region. A study of the relative distribution of the lavas of the region shows that it is only when they are grouped about San Francisco Mountain that the differentiation assumes an orderly character. The lavas will be taken up in order of decreasing acidity, beginning with the rhyolites.

THE RHYOLITES.

The six analyses of rhyolites, with which are included the biotite dacites of Kendrick and O'Leary peaks because of their similar texture and mineral composition, represent all the distinctly different masses of this lava except Slate Mountain, 6 miles north of Kendrick Peak.

Analyses of rhyolite.

	1	2	3	4	5	6
SiO_2	74.0	74.0	74.2	67.0	68.8	74.9
Al_2O_3	13.1	13.2	13.7	16.5	15.2	13.1
Fe_2O_3	1.4	.5	.8	2.3	2.7	.5
FeO	1.2	.5	1.0	2.1	1.7	.8
MgO	Tr.	.1	.2	.5	.7	.2
CaO	.1	.6	.8	2.0	1.7	.3
Na_2O	5.8	4.2	4.9	5.1	4.4	5.6
K_2O	4.3	4.8	4.0	3.3	3.7	4.3
TiO_2	.1	....	.1	.4	.3	.1

1. San Francisco Mountain.
2. Sugarloaf Hill, 4 miles from San Francisco Mountain.
3. Marble Hill, 4 miles from San Francisco Mountain.
4. O'Leary Peak, 9 miles from San Francisco Mountain.
5. Kendrick Peak, 11 miles from San Francisco Mountain.
6. Sitgreaves Peak, 19 miles from San Francisco Mountain.

The lavas of Sugarloaf and Marble hills, which lie nearest to San Francisco Mountain, have almost the same composition as the rhyolite of that mountain. They are, however, poorer in iron and soda and richer in lime. This difference expresses itself mineralogically in that they have biotite as the characteristic calfemic mineral, whereas the lava of San Francisco Mountain, with an excess of alkalies over alumina, has riebeckite. The lavas of O'Leary and Kendrick peaks, which occur next in order from San Francisco Mountain, are distinctly more basic and in a normal manner—that is, silica and alkalies are lower, whereas alumina, iron, magnesia, lime, and titania are higher than in the lava of San Francisco Mountain. Thus far the lavas exhibit a common tendency to become more basic toward the periphery of the region. The lava at the most distant locality, Sitgreaves Peak, however, reverts to practically the same composition as that of the lava of San Francisco Mountain, the only noticeable difference being in lower iron. The lava of Slate Mountain, which with respect to its distance from San Francisco Mountain falls between Kendrick and Sitgreaves peaks, has not been analyzed. Mineralogically and texturally, however, it is identical with certain varieties of the lava of Sitgreaves Peak and presumably has a similar chemical composition. The peripheral lavas thus have essentially the same composition as the central (San Francisco Mountain) type, although the lavas which occupy an intermediate position are more basic in composition.

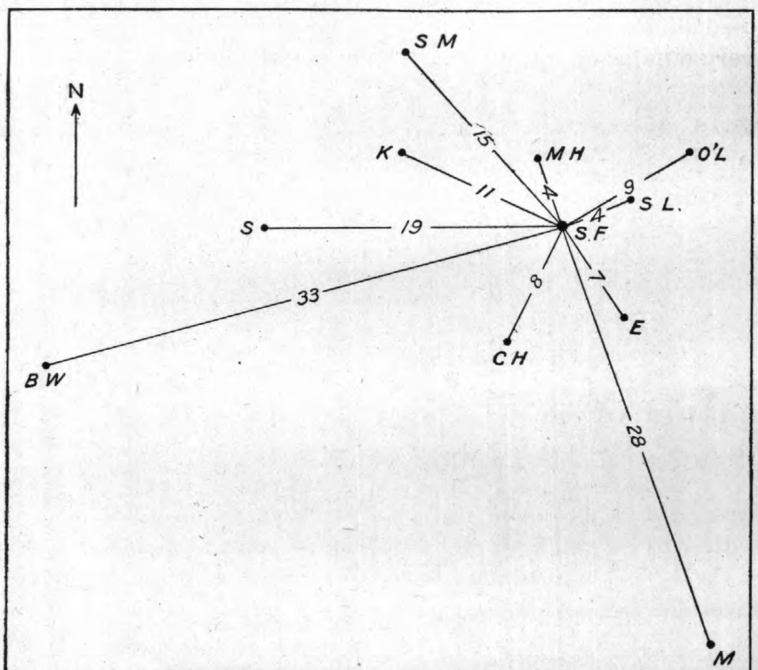


FIGURE 25.—Relative positions of cones of second period of eruption with respect to San Francisco Mountain. Distances in miles. BW, Bill Williams Mountain; CH, Crater Hill (Observatory Mesa); E, Elden Mountain; K, Kendrick Peak; M, Mormon Mountain; MH, Marble Hill; O'L, O'Leary Peak; S, Sitgreaves Peak; SF, San Francisco Mountain; SM, Slate Mountain; SL, Sugarloaf Hill.

THE DACITES.

The six analyses of dacite represent all the important isolated masses of this lava except that of the Dry Lake Hills, which are situated between San Francisco and Elden mountains. The lava of this locality is, however, mineralogically and texturally identical with the adjacent dacites and presumably has a similar chemical composition.

Analyses of dacite.

	1	2	3	4	5	6
SiO_2	64.6	65.9	62.3	61.2	66.8	66.0
Al_2O_3	16.6	17.2	16.4	17.0	16.5	16.1
Fe_2O_3	2.6	2.6	2.9	2.4	1.4	2.3
FeO	2.4	2.2	3.3	3.3	1.8	1.8
MgO	.9	.9	2.1	2.7	1.3	1.5
CaO	3.1	2.6	3.8	3.9	3.1	3.6
Na_2O	5.1	4.5	4.3	3.9	4.7	4.7
K_2O	3.4	3.1	3.2	3.0	2.5	2.9
TiO_2	.8	.5	1.0	.9	.4	.7

1. San Francisco Mountain, No. 9.
2. Elden Mountain, 7 miles from San Francisco Mountain.
3. O'Leary Peak, 9 miles from San Francisco Mountain.
4. Kendrick Peak (average of Nos. 13 and 14), 11 miles from San Francisco Mountain.
5. Mormon Mountain, 28 miles from San Francisco Mountain.
6. Bill Williams Mountain, 33 miles from San Francisco Mountain.

The lava of Elden Mountain, distant 7 miles, has practically the same composition as the dacite of San Francisco Mountain. No essential change in composition, then, takes place in this direction. The lavas of O'Leary and Kendrick peaks, however, are distinctly more basic; silica and alkalies are lower, whereas iron, magnesia, and lime are higher. The dacites of Mormon and Bill Williams mountains, which are most distant from San Francisco Mountain, exhibit a partial reversion to the type at the center. Silica and soda are nearly the same as in the lava of San Francisco Mountain. The values for iron and potash are less than in the dacites at other localities, whereas magnesia and lime are intermediate between those at San Francisco and Elden mountains on the one hand and O'Leary and Kendrick peaks on the other. The lavas of Mormon and Bill Williams mountains, therefore, have much the same composition, on the whole, as the dacite of San Francisco Mountain and are slightly but distinctly more acidic than the lavas of O'Leary and Kendrick peaks.

The relation duplicates that observed among the rhyolites.

THE LATITES.

Related rocks of the latite type occur only at San Francisco and Mormon mountains and Crater Hill. The lava at Crater Hill has the smallest volume and has not been analyzed.

Analyses of latite.

	San Francisco Mountain.	Mormon Mountain (28 miles distant).
SiO_2	59.8	61.6
Al_2O_3	17.0	17.3
Fe_2O_3	3.0	2.2
FeO	3.6	2.7
MgO	2.1	2.5
CaO	4.1	4.9
Na_2O	4.5	5.1
K_2O	2.9	2.2
TiO_2	1.1	.7

The lava of Mormon Mountain has slightly higher silica, magnesia, lime, and soda and lower iron, potash, and titania, so that its general composition is very similar to that of the latite of San Francisco Mountain. The peripheral lava thus closely resembles the central one, as is true of the rhyolites and dacites.

THE ANDESITES.

Andesites proper occur only at San Francisco and Kendrick mountains, but the andesite-basalt of Bill Williams Mountain is included with them on the basis of textural and mineralogic similarity.

Analyses of andesite.

	1	2	3
SiO_2	57.6	56.5	51.5
Al_2O_3	17.1	16.3	[a]17.2
Fe_2O_3	3.1	2.9	3.8
FeO	5.2	5.1	6.1
MgO	2.8	4.1	[a]6.0
CaO	5.6	6.1	8.1
Na_2O	4.2	3.9	3.4
K_2O	2.1	2.2	1.7
TiO_2	1.6	1.5	1.5

[a] Substituted for values of 18.2 and 5.0. See p. 183.

1. San Francisco Mountain.
2. Kendrick Peak, 11 miles from San Francisco Mountain.
3. Bill Williams Mountain, 33 miles from San Francisco Mountain.

The lava of Kendrick Peak is perhaps a trifle more basic than that of San Francisco Mountain, the most noticeable difference being in the magnesia. The lava of Bill Williams Mountain, however, is clearly more basic in a normal manner—that is, silica and alkalies are lower and iron, magnesia, and lime are higher. The change in composition is not expressed as an arithmetical function of the distance from San Francisco Mountain, as the lava of Kendrick Peak is somewhat too acidic, nor can it be expressed, apparently, in any simple manner. On the other hand, were the andesite of Kendrick Peak relatively as basic as the rhyolite and dacite of that mountain compared with the corresponding lavas of San Francisco Mountain, it would approach very nearly the composition of the andesite-basalt of Bill Williams Mountain. The andesites thus become increasingly basic toward the periphery of the region, a relation which is at variance with the change exhibited by the other lavas of the second period of eruption.

SUMMARY AND CONCLUSIONS.

The rhyolites and the dacites, which have the widest distribution, and the latites have certain features in common. The lavas of O'Leary and Kendrick peaks, as compared with those of San Francisco Mountain, the eruptive center of the region, have lower silica and alkalies and higher iron, magnesia, and lime. On the other hand, the lavas of Sitgreaves Peak and Mormon and Bill Williams Mountains, broadly speaking, have (*a*) the same amounts of silica and soda as the lavas of San Francisco Mountain, (*b*) greater amounts of lime and magnesia than the lavas of San Francisco Mountain, but less than those of O'Leary and Kendrick peaks, and (*c*) less iron and potash than any of the more centrally located lavas. The lavas at the periphery of the region are thus in some respects more basic and in others more acidic than those at the center and in a broad way may be considered to have the same general composition. On the contrary, those lavas which occupy a position between the center and periphery are more basic. The andesites exhibit the opposite features. The lava which occupies an intermediate position has the same composition as the central type, but the peripheral lava is the most basic. All the changes in composition of the lavas are slight and might not be thought of as due to differentiation were they not common to the several groups of lavas.

It is, of course, a matter of inference why the lavas should exhibit this particular type of regional differentiation, in which the more basic lavas are situated intermediately between central and peripheral varieties of essentially similar composition. Of the several possible explanations only one will be suggested. It rests on the assumption that the lavas came from a common magmatic reservoir, and this assumption is believed to be correct. It is based on such evidence as the genetic relationship of the individual lavas, shown by their serial chemical and mineral as well as textural characters, and the homogeneity of the average lavas of the composite cones and of the entire second period of eruption.

This explanation supposes that the originally homogeneous magma rose under each cone to horizons somewhat above the general level of the roof of the reservoir in the intervening spaces, thus producing chambers in which differentiation took place. The San Francisco Mountain chamber is supposed to be of large size and to be tapped at its outer borders by the Kendrick and O'Leary vents (fig. 26). The lavas of San Francisco Mountain and those of the peripheral cones, such as Bill Williams Mountain, may be considered as drawn from corresponding parts of their respective chambers and as having similar compositions. Those of Kendrick and O'Leary peaks, on the contrary, would be drawn from the borders of the San Francisco chamber and, if the differentiation of the magma in this chamber were of the common type, would be more basic in composition.

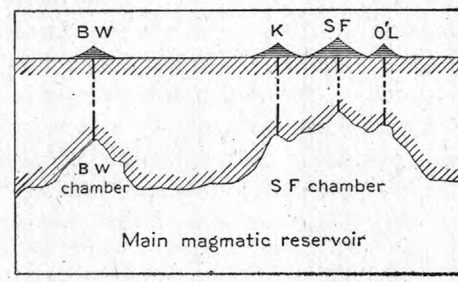


FIGURE 26.—Hypothetical form of magmatic reservoir. BW, Bill Williams Mountain; K, Kendrick Peak; O'L, O'Leary Peak; SF, San Francisco Mountain.

DIFFERENTIATION OF THE LAVAS IN TIME.

The broader features of the differentiation of the lavas or magma in time are touched upon in a succeeding section (p. 173); in this one will be considered the individual sequences of lavas which occur at the several composite cones of the second period of eruption. The magma of the first and third periods, so far as the erupted lavas indicate, remained undifferentiated; each period is represented by a single lava—a typical basalt—of uniform composition.

SAN FRANCISCO MOUNTAIN.

The sequence at the San Francisco volcano is composed of the lavas of five separate stages of eruption. The composition of the lavas and their order of eruption are as follows:

Chemical analyses of lavas of San Francisco Mountain.

	Pyroxene-hornblende latite.	Hyper-sthene-soda dacite.	Biotite-hornblende dacite.	Riebeckite-soda rhyolite.	Augite andesite.
SiO_2	59.8	64.6	66.5	74.0	57.6
Al_2O_3	17.0	16.6	16.6	13.1	17.1
Fe_2O_3	3.0	2.6	2.2	1.4	3.1
FeO	3.6	2.4	2.6	1.2	5.2
MgO	2.1	.9	.9	Trace.	2.8
CaO	4.1	3.1	2.8	.1	5.6
Na_2O	4.5	5.1	4.6	5.8	4.2
K_2O	2.9	3.4	3.4	4.3	2.1
TiO_2	1.1	.8	.8	.1	1.6
P_2O_5	.4	.2	.2	Trace.	.4
Specific gravity: Measured	2.69	2.66	2.56	2.38	2.74
Specific gravity: Calculated	2.85	2.74	2.70	2.66	2.91

The sequence begins with a latite, a lava of intermediate composition, proceeds through dacites to a soda rhyolite in the fourth stage, and ends with an andesite, the most basic rock of the series. It is thus one of increasing acidity, terminating with an abrupt drop to maximum basicity. The specific gravities vary indirectly as the composition of the lavas, decreasing progressively from the first through the fourth stage and increasing in the fifth. This is best shown by the calculated specific gravities for holocrystalline rocks in which variations due to differing degrees of crystallinity are eliminated. The changes among the oxides are normal—that is, as the lavas become more acidic, silica and alkalies increase, and iron, magnesia, lime, titania, phosphoric pentoxide, and in part alumina decrease, whereas the reverse relation holds between the rhyolite of the fourth and the andesite of the fifth stages. The lavas of the second and third stages have practically the same chemical composition, but show a slight difference in mineral composition, so that the sequence is composed of four distinct chemical types, although five separate stages of eruption are recorded in the volcano.

It is not possible to determine exactly further details in regard to the character of the differentiation that took place. It would seem, however, as if the interval between successive stages should depend somewhat on the extent to which the lavas differ in composition. Thus it seems reasonable to suppose that the interval between the second and third stages was very brief, because the lavas of these two stages are identical in composition. On the other hand, the andesite of the fifth stage rests, under peak F, upon a bed of biotite-hornblende dacite pumice, which indicates either that the interval between the third and fifth stages was short or that erosion was weak. The interval between the rhyolite and andesite (fourth and fifth) stages was, of course, still shorter, and the impression is that it was considerably less than that between the first and fourth stages and perhaps as short as the interval between the first and second stages. That is, the magma changed from a rhyolite to an andesite in a shorter time than was required for the change from a latite to a rhyolite or from a latite to a dacite. The rate of change was thus actually variable and not a linear function of the composition of the lavas, as the change from rhyolite to andesite represents a greater change in composition than that from latite to rhyolite or dacite. This impression is based on rough estimates of the apparent relative interstage erosion of the cone; these might be considerably modified by more detailed study.

KENDRICK PEAK.

The Kendrick Peak sequence is composed of lavas belonging to four separate stages of eruption. Two of the lavas, however, have nearly the same composition, so that it is made up of but three distinctly different chemical types. The composition of the lavas and their order of eruption is as follows:

Chemical analyses of lavas of Kendrick Peak.

		Biotite dacite.	Pyroxene dacite.	Hypersthene dacite.	Augite andesite.
SiO_2		68.8	62.0	60.4	56.5
Al_2O_3		15.2	17.0	17.0	16.3
Fe_2O_3		2.7	2.7	2.1	2.9
FeO		1.7	2.7	3.9	5.1
MgO		.7	2.4	3.0	4.1
CaO		1.7	4.0	4.4	6.1
Na_2O		4.4	4.0	3.8	3.9
K_2O		3.7	3.1	3.0	2.2
TiO_2		.3	.9	1.0	1.5
P_2O_5		.1	.2	.2	.3
Specific gravity	Measured	2.48	2.59	2.75	2.77
	Calculated	2.71	2.80	2.86	2.94

The series begins with a biotite dacite and proceeds through dacites of more basic composition to a true andesite. It is therefore one of continuously increasing basicity. The specific gravities, on the other hand, continuously increase from the beginning to the end of the series. The changes in composition are nearly normal; as the lavas become more basic, silica and potash decrease and ferrous iron, magnesia, lime, titania, and phosphoric pentoxide increase. One exception is alumina, which is constant in the dacites and the andesite, and if the pronounced general change in composition from the biotite dacite to the andesite is considered soda and ferric iron may also be regarded as constant. The lavas of the second and third stages have nearly the same composition, although the lava of the latter stage is a trifle more basic than that of the former, as shown by lower silica and higher ferrous iron, lime, and magnesia. The difference is slight and presumably indicates a brief interval between the two stages. A like similarity exists between the lavas of the second and third stages in San Francisco Mountain, and this relation, occurring in closely related rocks, is of peculiar significance in correlating the sequences of these two cones. The lavas at Kendrick Peak and San Francisco Mountain are genetically related and not markedly different in composition, although those at the former locality are somewhat more basic as the result of regional differentiation. It is interesting therefore to observe that the sequence at Kendrick Peak, only 11 miles from San Francisco Mountain, is essentially the reverse of the sequence at the latter volcano.

O'LEARY PEAK.

The sequence at O'Leary Peak is composed of two distinctly different lavas representing an equal number of eruptive stages. The composition of the lavas and their order of eruption is as follows:

Chemical analyses of lavas of O'Leary Peak.

		Biotite dacite.	Horn-blende dacite.
SiO_2		67.0	62.3
Al_2O_3		16.5	16.4
Fe_2O_3		2.3	2.9
FeO		2.1	3.3
MgO		.5	2.1
CaO		2.0	3.8
Na_2O		5.1	4.3
K_2O		3.3	3.2
TiO_2		.4	1.0
P_2O_5		.1	.2
Specific gravity	Measured	2.48	2.73
	Calculated	2.59	2.85

The change in this series is one of increasing basicity. It is very nearly normal in character. In the more basic lava silica and soda are lower, whereas iron, magnesia, lime, titania, phosphoric pentoxide, and also the specific gravity are higher. The exceptions are in alumina and potash, which are constant. The sequence at O'Leary Peak, located 9 miles from San Francisco Mountain, is of the same type as that at Kendrick Peak and is the reverse of the San Francisco Mountain sequence.

BILL WILLIAMS MOUNTAIN.

The sequence at the Bill Williams cone is composed of two lavas of decidedly different composition representing the same number of eruptive stages. The composition of the lavas and their order of eruption is:

Chemical analyses of lavas of Bill Williams Mountain.

		Augite andesite-basalt.	Horn-blende-soda dacite.
SiO_2		51.5	66.0
Al_2O_3		[a] 17.2	16.1
Fe_2O_3		3.8	2.3
FeO		6.1	1.8
MgO		[a] 6.0	1.5
CaO		8.1	3.6
Na_2O		3.4	4.7
K_2O		1.7	2.9
TiO_2		1.5	.7
P_2O_5		.4	.2
Specific gravity	Measured	2.82	2.53
	Calculated	3.03	2.70

[a] Substituted for values of 18.2 and 5.0. See p. 183.

The first lava is an andesite-basalt, the second a soda dacite. The sequence is, therefore, from a basic lava to one of intermediate composition. The change in composition is normal. In the more acidic rock silica and alkalies are higher, whereas the other oxides, as well as the specific gravity, are lower. The sequence at this cone on the border of the field, 33 miles from San Francisco Mountain, is of the same type as that at the latter cone.

MORMON MOUNTAIN.

The Mormon Mountain sequence, like those at O'Leary Peak and Bill Williams Mountain, is composed of two different lavas representing the same number of eruptive stages. The composition of the lavas and their order of eruption is as follows:

Chemical analyses of lavas of Mormon Mountain.

	Pyroxene latite.	Horn-blende-soda dacite.
SiO_2	61.6	66.8
Al_2O_3	17.3	16.5
Fe_2O_3	2.2	1.4
FeO	2.7	1.8
MgO	2.5	1.3
CaO	4.9	3.1
Na_2O	5.1	4.7
K_2O	2.2	2.5
TiO_2	.7	.4
P_2O_5	.2	.1
Specific gravity, Measured	2.63	2.48
Specific gravity, Calculated	2.81	2.72

The first lava is a latite, the second a soda dacite. The sequence is, therefore, from a rock of intermediate composition to one that is more acidic. The change in composition is nearly normal. In the more acidic lava silica and potash are higher, whereas iron, magnesia, lime, titania, and phosphoric pentoxide, as well as the specific gravity, are lower. Alumina, from its relatively greater amount, may be regarded as constant. Soda is a trifle lower, but the sum of the alkalies is the same in the two rocks.

The Mormon Mountain sequence is the only one in which the order of the lavas is in doubt. The dacite is considered younger than the latite on account of its somewhat fresher condition. Mormon Mountain is located 28 miles from San Francisco Mountain and its sequence, if correctly determined, is of the same type as those at Bill Williams and San Francisco mountains.

SUMMARY AND CONCLUSIONS.

The San Franciscan sequences, when regarded broadly, without reference to the exact composition of the individual lavas, fall into two groups. One group is composed of those sequences in which the lavas become successively more acidic; the other contains the sequences of a reverse character, the lavas becoming successively more basic. The San Francisco Mountain sequence actually possesses features common to both groups but is included in the first, as the tendency of most of the lavas is toward increasing acidity. As thus classified the sequences of San Francisco, Bill Williams, and Mormon mountains belong to the first group and those of Kendrick and O'Leary peaks belong to the second.

Thus the same grouping of the composite cones results from a study of the lavas with respect to their differentiation in both time and space. The similar sequences of the central and peripheral cones are composed of lavas of the same general composition, whereas the reverse sequences of the intermediately situated cones are made up of related lavas of a more basic composition. This similar grouping of the composite cones is suggestive of a causal relationship between the differentiation of the magma in time and in space.

It is also an interesting fact that no two of the sequences are alike, although all are composed of genetically related lavas. This is illustrated by the following table:

Sequences of lavas in the San Franciscan volcanic field.

	San Francisco Mountain.	Kendrick Peak.	O'Leary Peak.	Bill Williams Mountain.	Mormon Mountain.
1	Latite	Biotite dacite	Biotite dacite	Andesite basalt	Latite.
2	Soda dacite	Dacite	Dacite	Soda dacite	Soda dacite.
3	Dacite	Dacite			
4	Soda rhyolite	Andesite			
5	Andesite				

The five sequences have but a single lava in common, namely, the dacite, and this furnishes a basis for their comparison. The lavas of Kendrick and O'Leary peaks, which correspond to the soda dacites of the other cones, are slightly more basic as the result of regional differentiation and are classified simply as dacites. Similarly the biotite dacites of Kendrick and O'Leary peaks are the equivalents of the soda rhyolite of San Francisco Mountain, and the andesite-basalt of Bill Williams Mountain is related to the andesites of San Francisco Mountain and Kendrick Peak.

It will be seen that the O'Leary Peak and Bill Williams Mountain sequences may be considered as incomplete representatives of the San Francisco Mountain sequence in reversed order. Thus, at O'Leary Peak the andesite and latite are absent and at Bill Williams Mountain the rhyolite and latite. The Mormon Mountain sequence may be considered an incomplete direct representative of the San Francisco Mountain sequence, the rhyolite and andesite being absent. The Kendrick Peak sequence, on the contrary, can not be explained as an incomplete reversed San Francisco Mountain sequence, for the last member is an andesite instead of a latite. Still greater incompleteness of sequence is illustrated by the cones which are composed of but a single lava. The principal of these cones are Sitgreaves Peak, formed entirely of rhyolite; Elden Mountain, consisting of soda dacite; and Crater Hill, which consists of latite. No simple cone of andesite is known.

It is evident from the foregoing table that the sequences can not be arranged to indicate the contemporaneous eruption of similar lavas, except dacites, at the several cones. Consequently it must be accepted as a fact that lavas of diverse composition were erupted at the same time at various points throughout the region. It seems reasonable to conclude, however, that the differences in the composition of the individual lavas, as well as in their order of eruption at each cone, were due to purely local causes, as the average lavas of all the composite cones have practically the same composition.

It is to be presumed that there can be incompleteness and reversal of the broader periods of eruption similar to that shown by the sequences of a single period. Incompleteness of the broader periods is actually shown at several localities in the Plateau country, as on the Uinkaret Plateau and the Black Mesa, by the presence only of basalts corresponding to those of the first and third periods of the San Franciscan region, the lavas of intermediate and acidic composition being absent. Still greater incompleteness of the broad periods is found in the Rabbit Ear Mountains, north of Holbrook, Ariz., where only the basalt of the first period is present. Examples of reversal in the order of the broader periods of activity are not known in this general region, although they may be found in the Mount Taylor volcanic field of New Mexico, where the series of lavas closely resembles that of the San Franciscan region.

DIFFERENTIATION OF THE MAGMA.

Before considering possible schemes for explaining the observed sequence of eruptions in the San Franciscan volcanic field some idea should be formed as to the location of the zone within which the differentiation of the magma may have taken place and what proportion the volume of erupted lavas bears to the total volume of the parent magma.

ZONE OF DIFFERENTIATION.

It is improbable that the differentiation of the magma occurred in what may properly be considered the conduits of the volcanoes because of their too small volume. A hypothetical conduit may be conceived as having the form of a right cylinder one-fourth of a mile in diameter, which is the average size of the vents of the large San Franciscan cones, and a maximum length of 30 miles. The volume of this conduit would be 1.5 cubic miles, which is considerably less than the volumes of the principal lava masses of the region and very much less than those of the latite and dacite of San Francisco Mountain. But the conduit would be occupied by at least two and possibly more products of differentiation unless all the separated parts but one sank into the main reservoir below. Consequently the space available for a single homogeneous portion of the magma would be considerably less than the total volume of the conduit, thus increasing its discrepancy with the observed volumes of the erupted lavas. It is not difficult to think of a volcanic vent of this size as existing in the zone of fracture, where the magma may force its way to the surface along definite lines of dislocation, or in the upper part of the zone of flowage, where shear planes are strongly developed, but it may be questioned whether it could exist at greater depths. The length of the conduit proper might thus be not more than 10 miles and its volume 0.5 cubic mile, so that it becomes very much less in volume than most of the lava masses of the large cones. These considerations indicate that the differentiation of the magma could not well have occurred in the conduits of the volcanoes, properly speaking, even if their length could possibly have been as great as 30 miles. This conclusion holds generally true, as there are bodies of each variety of lava whose volume is greater than that of the conduit through which they were erupted.

It might also be supposed that the diverse sequences of lavas erupted during the second period of activity resulted from the differentiation of local pockets (laccolithic bodies) of magma situated at horizons intermediate between a deep-seated reservoir and the surface. The volume of lava at each cone would then be approximately equal to the volume of the laccolithic pocket and each portion of the differentiated magma would have to be erupted independently. It is probably true that volcanic eruptions may be directly associated with laccolithic intrusions, and such an association is suggested by the Marble Hill laccolith, but there are no observations to support the idea that a diverse sequence of lavas can originate through the differentiation of a laccolithic body of magma. In addition, the evidence of this region and of the surrounding country points to the intrusion of such small bosses of igneous rock at a horizon so near the surface as to produce distinct doming of the strata, a feature not associated with any of the volcanic cones. Evidently the origin of the various sequences of lavas of the composite cones through the differentiation of the magma in laccolithic bodies calls for so special a mechanism in the process of eruption as to make this method highly improbable.

It is necessary to suppose, therefore, that differentiation occurred in batholithic bodies of magma so deeply seated as to produce no doming of the strata at the surface, or in a common and distinctly deep-seated reservoir. This idea has already been expressed in the explanation of the differentiation of the magma in space (pp. 168–169). The difference between these two conceptions is not radical, for the batholiths are considered as irregular offshoots from a main magmatic reservoir which in some manner forced their way to higher horizons. A minimum depth of 30 miles is assigned to the main reservoir, for at that depth, using a gradient of 75° F. to the mile, the earth's internal temperature would be 2,250°, or about the average melting point of igneous rocks. The depth of origin could not be much less than this for a permanent body of magma covering a wide area, as a lower temperature would eventually bring about solidification. A minimum depth of 10 miles is assigned to the batholiths in order to keep them within the upper part of the zone of flowage, for at about that horizon the magma is considered as being able to establish outlets of small size to the surface. Whichever of these two zones may have been the actual seat of the differentiation of the magma, such evidence as is furnished by the serial chemical and mineral compositions, the specific gravities, and other characters of the lavas and probably the homogeneity of the average lavas of the composite cones clearly indicate a primary origin in a common magmatic reservoir.

RELATIVE PROPORTION OF THE ERUPTED LAVAS TO THE TOTAL VOLUME OF THE MAGMA.

In order to form an idea of what proportion the erupted lavas bear to the total volume of the magma it is necessary to make some assumption as to their origin. It will be supposed, therefore, that they have been derived from a common magmatic reservoir or from batholithic offshoots. The term reservoir, as well as batholith, is used only in a general sense to express the idea of the existence of a deep-seated mass of magma of indeterminate form.

The total volume of the erupted lava in the region may be placed at 110 cubic miles. If the lavas originated in a common reservoir it may be supposed that this reservoir had an area about equal to that covered by the cones of the second and third periods of activity, or approximately 1,200 square miles. If, therefore, the erupted portion of the magma was uniformly distributed over this area it would have a thickness of about 500 feet, which would equal, say, 0.002 of the average diameter of the reservoir. A less discordant result, although of the same character, is obtained on the assumption that the lavas were derived from batholithic chambers. This is sufficient to show, without a statement as to what might be considered a reasonable proportion between the horizontal and vertical dimensions of the reservoir, that the volume of the erupted lavas represents only a fraction of the total volume of the parent magma.

DEGREE OF SIMILARITY BETWEEN THE ERUPTED LAVAS AND THEIR MAGMAS.

The question next arises as to the degree of similarity that may exist between the composition of the average lavas of the three general periods of eruption and of the entire region, and that of the magmas from which they were derived. The degree of similarity would appear to depend to some extent on the character of the differentiation, whether it was simple or complex, or whether differentiation was lacking. Where but a single lava is erupted over a wide area and through a considerable interval of geologic time it may be supposed that it represents an undifferentiated magma of the same composition. For if the magma underwent differentiation the chances would seem to be much in favor of this fact being expressed at some time during the period by the eruption of lava of variant composition. During the first and third periods of activity in the San Franciscan region only basalts of very uniform composition were erupted. These basalts, then, may be taken as closely approximating the composition of their parent magma.

It would appear that as the number of different lavas erupted during any one period increases the chance of their average composition being the same as that of the parent magma should decrease, for it is improbable that the various lavas would be erupted in the same relative amounts that existed in the reservoir. Yet it is a significant fact that in the San Franciscan volcanic field the average lavas of the composite cones and the average lava of the entire second period of eruption, to which they belong, have practically the same composition—that is, they may be considered as strictly homogeneous. Although this is not direct proof that the magma of the second period was of this same composition—indeed, in the nature of things, direct proof is not obtainable—it is highly suggestive of such a condition.

There appears to be, therefore, some justification for assuming that the composition of the average lava of each of the three general periods of eruption in the San Franciscan region represents rather closely that of its parent magma. But to assume further that the average lava of the three periods represents the composition of the parent magma of the region is, perhaps, raising the degree of probability to an unwarranted extent and need not be insisted upon. It is, however, interesting to note that in this region, where the individual lavas approach rather closely in composition to the commonest rock families, their weighted average shows a corresponding similarity to the average igneous rock of the earth's crust. This evidently follows from the fact that the weighted average of the four reference types of the rhyolite-granite, trachyte-syenite, andesite-diorite, and basalt-gabbro families, comprising in all 880 analyses, gives the composition of the average igneous rock of the earth's crust with practically the same degree of accuracy as do the 1,811 analyses used by Washington.

It may be concluded, therefore, that, although the erupted lavas represent only a fraction of the total volume of the magma, when each period of eruption began the magma was in a homogeneous condition and of the same composition as the average lava of the period. It is also possible that the original magma may have had the composition of the average lava of the region. Certain considerations, which are given in the following section, indicate, however, that it probably did not have this composition.

SCHEMES OF DIFFERENTIATION.

The general sequence of eruptions in the San Franciscan volcanic field, as represented by the average lavas of the three general periods of activity, seems best explained by either of two different schemes which are independent of the initial composition of the magma. They may be expressed graphically as in figure 27.

FIRST SCHEME.

According to the first and simplest scheme the original magma is supposed to split up into three portions, one for each general period of eruption. The basaltic magmas of the first and third periods remain undifferentiated, but the dacitic magma of the second period separates into rhyolites, dacites, latites, and andesites. If the initial composition of the magma is supposed to be andesitic, corresponding to the average rock of the region, the first differentiation product is more basic, the second is more acidic, and the third has the same composition as the first. This sequence is not impossible, as is indicated by the character of the secondary sequences of the second period of activity.

This first scheme may also be interpreted on the assumption that the original magma had a basaltic composition. The lavas of the first and third periods would then be undifferentiated portions of the original magma, whereas that of the second period would be a more acidic separation product, which further split up into fractional parts more acidic and basic than itself. It is, of course, necessary to suppose that the dacitic portion of the second period was very small compared with the total volume of the magma, as its separation caused no perceptible change in the composition of the original magma. It is true that the basalt of the third period is a trifle more basic than that of the first, but this fact can hardly be given any weight, as the analyses represent the composition of only minute fractions of their respective rock masses, and the differences are no greater than would be expected to occur in a single body of lava. On the whole, this interpretation of the first scheme seems more plausible than the one which assumes an andesitic composition for the magma.

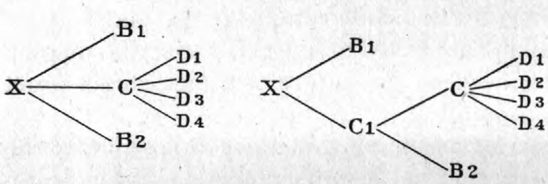


FIGURE 27.—Schemes of differentiation of the magma in the San Franciscan volcanic field: X, initial magma; B1, magma (basaltic) of first period; B2, magma (basaltic) of third period; C, magma (dacitic) of second period; C1, magma (andesitic) of which C and B2 are the differentiation products; D1, D2, D3, and D4, differentiation products of C.

SECOND SCHEME.

According to the second scheme the initia magma is supposed to separate into two main portions, B1 and C1. B1 is erupted in an undifferentiated condition as the basalt of the first period. C1 splits into C, the dacitic magma of the second period (which undergoes a further separation into rhyolites, dacites, latites, and andesites), and B2, the basaltic magma of the third period, which is erupted without further differentiation. As in the first scheme, the original magma may be considered either as andesitic or as basaltic in composition. If the latter, the basalt of the first period would be looked upon as an undifferentiated portion of the original magma.

In favor of the second scheme is the close relationship that exists between the distribution of the small basaltic cones of the third period and the large volcanoes of the second period of activity. At Kendrick Peak, in particular, there is a very intimate association of the lavas of the two periods, not less than six basalt vents being situated on the slopes of the large cone. Indeed, a study of Kendrick Peak independently of the remainder of the field would lead to the conclusion that the basalt represents a direct continuation of the volcanic activity of the main cone. In striking contrast with this distinct grouping of the cones of the second and third periods and the relatively small area covered by their lavas is the widespread distribution of the basalt of the first period of eruption, which has necessitated drawing arbitrary boundaries for the field on the west and south.

CONCLUSION.

As an explanation of the sequence of eruptions in the San Franciscan volcanic field, taken by itself, the second scheme of differentiation seems preferable to the first, but some doubt is felt of the correctness of this choice when the volcanic phenomena of the surrounding country are studied. Although there are some regions where three periods of eruption, corresponding to those of the San Franciscan region, are represented, a larger number of regions are characterized only by basaltic lavas, which represent either the first or the first and third periods of activity in the San Franciscan field. The basaltic lavas not only have a much greater volume than those of intermediate and acidic composition, but are very much more widely distributed. All these lavas are of Tertiary and Quaternary age. The only other period of volcanic activity within this general region occurred during pre-Cambrian time, and it is interesting to note that the lava then erupted was a basalt.[1] These conditions suggest that the magma underlying what is now the southern Plateau country actually has the composition of a basalt and that the occasional occurrence of a period during which lavas of intermediate and acidic composition were erupted was the result of special causes of a local nature. If such was the case, the first scheme of differentiation, having a basaltic composition for the magma, would be preferable to the second scheme.

That a basaltic composition may be preferred for the primary magma of the San Franciscan region can not, however, be considered as evidence in support of the theory that the universal magma of the earth has a similar composition. If the widespread eruption of a homogeneous lava through a considerable interval of geologic time is a true criterion for determining the character of the parent magma, it must be concluded that the universal magma of the earth is heterogeneous, for there are notable contrasts in the composition of rocks of different petrographic provinces.

CHEMICAL CHARACTERS.

CHEMICAL ANALYSES.

The chemical analyses of the lavas of the San Franciscan volcanic field are collected in the following table. They are arranged approximately in order of increasing basicity, so that their general character and the changes in composition may be readily seen. They represent all the different rock varieties that occur in the region, and none have hitherto been published. The only published analysis of a rock from this region is that of a "typical hypersthene andesite,"[2] but this is not included in the list, as the exact locality of the specimen is unknown, and it is certainly duplicated by one of the author's analyses, most presumably that of the lava of Elden Mountain.

The analyzed material was entirely fresh except Nos. 1, 9, 10, 11, 17, 20, and 22. In these specimens the calfemic minerals were partly altered, which gave rise to incorrect analytic values for ferric and ferrous iron as compared with those of fresh rock. Corrected values for these two oxides, obtained from the calculated modes and very nearly representing the true values for the fresh rock, are given in parentheses. Analysis No. 22 is also given with 4.25 per cent of infiltrated calcite removed, and in this the values for ferric and ferrous iron have been obtained partly from the mode and partly by comparison with the basalt of Kendrick Peak. The corrected values for ferric and ferrous iron have been used in dealing with the serial chemical characters of the lavas and in calculating the composition of the various average lavas, as for these purposes it was essential to use the original composition of the rocks.

[1] Walcott, C. D., Pre-Cambrian igneous rocks of the Unkar terrane, Grand Canyon of the Colorado, Arizona: Fourteenth Ann. Rept., U. S. Geol. Survey, pt. 2, 1894, p. 497.

[2] Bull. U. S. Geol. Survey No. 228, 1904, p. 202; also p. 125 of this report.

Chemical analyses of the lavas of the San Franciscan volcanic field.

I. Individual lavas.

No.	Name	Position in quantitative system.	Locality.	SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	MgO.	CaO.	Na_2O.	K_2O.	H_2O+.	H_2O-.	CO_2.	TiO_2.	ZrO_2.	P_2O_5.	SO_3.	Cl.	F.	MnO.	SrO.	BaO.	Li_2O.	Sum.	Sp. gr.
1	Biotite rhyolite.........	Liparose....	Sugarloaf Hill...	74.02	13.20	0.75 (.5)	0.29 (.5)	0.06	0.56	4.18	4.82	1.86	....	None.	0.02	Undet.	Undet.	......	Trace.	......	Trace.	......	......	......	99.76	.....
2	Biotite-soda granite porphyry.	Kallerudose.	Marble Hill.....	74.23	13.65	.84	1.04	.23	.75	4.87	3.96	.19	....	None.	.08	Pres.	Undet.	......	Trace.	Undet.	Trace.	......	......	......	99.84	2.56
3	Biotite-soda rhyolite....	Kallerudose.	Sitgreaves Peak.	74.93	13.11	.51	.77	.23	.30	5.64	4.28	.28	0.04	None.	.07	Pres.	Undet.	......	Trace.	Undet.	Trace.	......	......	......	100.16	2.37
4	Riebeckite-soda rhyolite.	Kallerudose.	San Francisco Mountain.	74.01	13.08	1.38	1.21	Tr.	.13	5.78	4.31	.16	.10	None.	.11	Pres.	Undet.	......	Trace.	Undet.	Trace.	......	......	......	100.27	2.38
5	Reibeckite-soda granite porphyry.	Kallerudose.	San Francisco Mountain.	74.19	12.85	1.60	.98	.11	.12	5.86	3.98	.10	.16	None.	.09	Pres.	Undet.	......	Trace.	Undet.	Trace.	......	Trace.	Trace.	100.04	2.66
6	Biotite dacite...........	Lassenose...	Kendrick Peak..	68.76	15.22	2.72	1.74	.72	1.68	4.42	3.73	.66	.16	None.	.31	Undet.	0.15	None.	Trace.	Undet.	Trace.	......	Undet.	......	100.27	2.48
7	Biotite dacite...........	Lassenose...	O'Leary Peak...	66.98	16.47	2.31	2.14	.52	2.02	5.05	3.32	.59	.12	None.	.35	Undet.	.13	None.	Trace.	Undet.	Trace.	......	Undet.	......	100.00	2.48
8	Biotite-hornblende dacite.	Lassenose...	San Francisco Mountain.	66.50	16.55	2.25	2.38	.87	2.75	4.55	3.36	.16	.12	None.	.59	Undet.	.19	None.	Trace.	Undet.	Trace.	......	None.	......	100.47	2.56
9	Hypersthene-soda dacite.	Lassenose...	San Francisco Mountain.	64.60	16.60	2.62 (2.3)	2.38 (2.66)	.93	3.06	5.12	3.43	.10	.18	None.	.80	Undet.	.18	None.	Trace.	Undet.	0.06	None.	.04	......	100.10	2.66
10	Hypersthene-hornblende-soda dacite.	Lassenose...	Elden Mountain.	65.92	17.12	4.68 (2.55)	.15 (2.15)	.86	2.59	4.49	3.10	.26	.10	None.	.51	Undet.	.25	None.	Trace.	Undet.	Undet.	......	Undet.	......	100.05	2.60
11	Hornblende-soda dacite.	Lassenose...	Mormon Mountain.	66.85	16.48	2.96 (1.4)	.43 (1.8)	1.27	3.06	4.70	2.48	1.66	.09	None.	.39	Undet.	.11	None.	Trace.	Undet.	Undet.	......	Undet.	......	100.48	2.48
12	Hornblende-soda dacite.	Lassenose...	Bill Williams Mountain.	65.99	16.14	2.28	1.84	1.47	3.57	4.73	2.90	.67	.15	None.	.68	Pres.	.15	None.	Trace.	Undet.	Undet.	......	Undet.	......	100.57	2.53
13	Pyroxene dacite.........	Tonalose....	Kendrick Peak..	61.96	17.04	2.71	2.66	2.41	3.99	4.00	3.10	.89	.22	None.	.87	Undet.	.22	None.	Trace.	Undet.	Trace.	......	Undet.	......	100.06	2.59
14	Hypersthene dacite.....	Tonalose....	Kendrick Peak..	60.40	17.01	2.05	3.92	2.97	4.45	3.85	2.97	.70	.11	None.	1.00	Undet.	.22	None.	Trace.	Undet.	Undet.	......	Undet.	......	99.65	2.75
15	Hornblende dacite......	Dacose......	O'Leary Peak...	62.32	16.40	2.87	3.32	2.10	3.83	4.26	3.25	.62	.08	None.	.96	Undet.	.20	None.	Trace.	Undet.	Undet.	......	Undet.	......	100.23	2.59
16	Pyroxene latite.........	Tonalose-andose.	Mormon Mountain.	61.60	17.34	2.22	2.73	2.46	4.92	5.10	2.16	.51	.12	None.	.73	Undet.	.24	None.	Trace.	Undet	Undet.	......	Undet.	......	100.13	2.63
17	Pyroxene-hornblende latite.	Dacose-akerose-tonalose-andose.	San Francisco Mountain.	59.76	17.03	5.99 (3.0)	.90 (3.6)	2.11	4.06	4.50	2.94	.43	.64	None.	1.07	Undet.	.35	None.	Trace.	Undet.	.10	.03	.14	......	100.05	2.69
18	Augite andesite.........	Andose......	San Francisco Mountain.	57.64	17.07	3.07	5.15	2.80	5.55	4.20	2.14	.05	.09	None.	1.57	Undet.	.37	None.	Trace.	Undet.	.08	None.	.05	......	99.85	2.74
19	Augite andesite.........	Andose......	Kendrick Peak..	56.51	16.28	2.93	5.13	4.12	6.10	3.94	2.18	.40	.10	None.	1.50	Undet.	.30	None.	Trace.	Undet.	.08	......	Undet.	......	99.57	2.77
20	Augite andesite-basalt...	Andose......	Bill Williams Mountain.	51.53	18.21	4.59 (3.8)	5.46 (6.1)	4.99	8.05	3.45	1.67	.31	.20	None.	1.50	Undet.	.36	None.	Trace.	Undet.	.10	......	Undet.	......	100.42	2.82
21	Hornblende-soda andesite-basalt.	Andose......	Bill Williams Mountain.	53.97	16.00	4.56	3.63	6.36	7.47	4.38	1.23	1.31	.03	None.	1.46	Undet.	.10	None.	Trace.	Undet.	Undet.	......	Undet.	......	100.50	.....
22	Augite basalt...........	Auvergnose.	Cedar Ranch Mesa.	47.70 49.73	15.30 15.96	5.93 (3.5)	4.85 (7.5)	7.31 7.62	11.83 9.85	2.46 2.56	.61 .64	.34 .35	.10 .10	1.87	1.45 1.51	Undet. Undet.	.29 .31	None. None.	Trace. Trace.	Undet. Undet.	.46 .50	.02 .02	.09 .09	....	100.61 100.24	2.95
23	Augite basalt...........	Auvergnose.	Kendrick Peak..	47.41	16.35	3.37	7.72	8.55	10.45	2.50	.75	.11	.08	None.	1.54	Undet.	.49	None.	Trace.	Undet.	.27	Trace.	.04	......	99.94	2.95

II. Average lavas.

No.	Name	Position in quantitative system.	Locality.	SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	MgO.	CaO.	Na_2O.	K_2O.	H_2O+.	H_2O-.	CO_2.	TiO_2.	ZrO_2.	P_2O_5.	SO_3.	Cl.	F.	MnO.	SrO.	BaO.	Li_2O.	Sum.	Sp. gr.
A	Average rhyolite, of second period of eruption.	......	......	71.0	14.5	1.8	1.5	0.5	1.1	4.9	3.9	0.5	0.1	......	0.2	......	0.1	......	......	......	......	......	......	......	100.1	2.44
B	Average dacite, of second period of eruption.	......	......	64.7	16.6	2.5	2.4	1.2	3.2	4.8	3.3	.3	.1	......	.8	......	.2	......	......	......	0.1	......	......	......	100.2	2.62
C	Average latite, of second period of eruption.	......	......	59.9	17.1	2.9	3.5	2.2	4.1	4.6	2.9	.4	.6	......	1.0	......	.3	......	......	......	.1	......	0.1	......	99.7	2.68
D	Average andesite, of second period of eruption.	......	......	56.5	17.2	3.2	5.3	3.2	6.0	4.1	2.1	.1	.1	......	1.5	......	.3	......	......	......	.1	......	.1	......	99.8	2.76
E	Average basalt, of first and third periods of eruption.	......	......	48.8	16.1	3.4	7.6	8.0	10.1	2.5	.7	.2	.1	......	1.5	......	.4	......	......	......	.4	......	.1	......	99.9	2.95
F	Average lava, of entire second period of eruption.	......	......	63.8	16.3	2.6	2.8	1.5	3.3	4.7	3.2	.4	.3	......	.8	......	.3	......	......	......	.1	......	.1	......	100.2	2.60
G	Average lava, of entire region.	......	......	56.7	16.3	3.0	5.1	4.6	6.5	3.7	2.0	.3	.2	......	1.1	......	.3	......	......	......	.2	......	.1	......	100.1	2.76

MOLECULAR RATIOS OF THE PRINCIPAL OXIDES.

The molecular ratios, for convenience in future references, are assembled in the subjoined table. They have necessarily been used throughout the discussion of the serial chemical characters of the lavas, as the true relation of the oxides to each other is only thus brought out. The discussion of the serial mineral characters is also based on the molecular amounts of the several minerals, although as a matter of convenience the amounts are plotted in figure 32 (p. 194) according to percentage values. The modes of the lavas have been calculated in part from the molecular ratios of the oxides, in part from percentage values.

Molecular ratios of the principal oxides in the lavas of the San Franciscan volcanic field.

Individual lavas.

No.	SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	MgO.	CaO.	Na_2O.	K_2O.	TiO_2.	P_2O_5.	MnO.
1	1.234	0.129	(0.003)	(0.007)	0.002	0.010	0.067	0.051	....	....	....
2	1.237	.134	.005	.014	.006	.013	.078	.042	0.001	....	....
3	1.249	.129	.003	.011	.006	.005	.091	.046	.001	....	....
4	1.234	.128	.009	.017	None.	.002	.093	.046	.001	....	....
5	1.237	.126	.010	.014	.003	.002	.094	.042	.001	....	....
6	1.146	.149	.017	.024	.018	.030	.071	.039	.004	0.001	....
7	1.116	.161	.014	.030	.013	.036	.081	.035	.004	.001	....
8	1.108	.162	.014	.036	.022	.049	.073	.036	.007	.001	....
9	1.077	.163	(.014)	(.037)	.023	.055	.083	.036	.010	.001	0.001
10	1.099	.168	(.016)	(.030)	.021	.046	.073	.033	.006	.002	....
11	1.114	.162	(.009)	(.025)	.032	.055	.076	.026	.005	.001	....
12	1.100	.158	.014	.025	.037	.064	.076	.031	.008	.001	....
13	1.032	.167	.017	.037	.060	.071	.064	.033	.011	.002	....
14	1.007	.166	.013	.054	.074	.079	.062	.032	.012	.002	....
15	1.039	.161	.018	.046	.052	.068	.069	.035	.012	.001	....
16	1.026	.170	.014	.038	.062	.088	.082	.023	.009	.002	....
17	.996	.166	(.019)	(.050)	.053	.072	.073	.031	.013	.003	.001
18	.961	.168	.019	.072	.070	.099	.068	.023	.019	.003	.001
19	.942	.159	.018	.071	.103	.109	.063	.023	.018	.002	.001
20	.859	(.169)	(.024)	(.085)	(.150)	.144	.056	.018	.018	.003	.001
21	.900	.157	.029	.050	.159	.134	.071	.013	.018	.001	....
22	.829	.156	(.022)	(.104)	.191	.176	.041	.007	.019	.002	.006
23	.790	.160	.021	.107	.214	.186	.040	.008	.019	.004	.004
Average lavas.											
A	1.183	0.142	0.011	0.021	0.012	0.020	0.079	0.041	0.003	0.001	....
B	1.078	.163	.015	.033	.030	.057	.077	.035	.010	.001	0.001
C	.997	.168	.018	.049	.055	.073	.074	.031	.013	.002	.001
D	.942	.169	.020	.074	.080	.107	.066	.022	.019	.002	.001
E	.813	.158	.021	.106	.200	.180	.040	.007	.019	.003	.006
F	1.063	.160	.016	.039	.038	.059	.076	.034	.010	.002	.001
G	.945	.160	.019	.071	.115	.116	.060	.021	.014	.002	.003

ABSOLUTE CHEMICAL CHARACTERS.

The range in the percentages of the principal oxides are given in the following table and are compared with the extreme range of the corresponding oxides of igneous rocks which have the same silica range as the lavas of the San Franciscan volcanic field and with the percentages of the same oxides in the average igneous rock of the earth's crust. The range in the oxides for igneous rocks in general is based on the superior analyses in the Washington and Washington-Roth tables of analyses[1], and the composition of the average igneous rock of the earth's crust is that of Washington. The indefiniteness that attaches to a discussion of the absolute chemical characters of igneous rocks without reference to some standard will be recognized, and these two bases of comparison have been selected as offering different points of view.

Percentages of principal oxides in certain igneous rocks.

	1	2	3
SiO_2	47.4–74.9	48.0–78.0	57.8
Al_2O_3	12.8–17.3	1.0–35.0	15.7
Fe_2O_3	.5– 4.6	0–12.5	3.3
FeO	.3– 7.7	0–15.0	3.8
MgO	tr.– 8.6	0–35.0	3.8
CaO	.1–10.4	0–16.5	5.2
Na_2O	2.5– 5.9	0–12.5	3.9
K_2O	.6– 4.8	0–12.0	3.1
TiO_2	tr.– 1.6	0– 2.0	1.0
P_2O_5	tr.– .5	0– 1.5	.4
MnO	tr.– .5	0– .8	.2

[1] Prof. Papers U. S. Geol. Survey Nos. 14 and 28.

1. Minimum and maximum percentages of principal oxides of lavas of the San Franciscan volcanic field.
2. Same for igneous rocks in general which have similar silica range as the lavas of the San Franciscan volcanic field.
3. Average igneous rock of the earth's crust.

The range in silica is large; a study of the analyses in the Washington and Washington-Roth tables shows that 95 per cent of all igneous rocks fall within it. The minimum silica is nearer that of the average igneous rock of the earth's crust than the maximum. The rhyolites being excluded, the silica of the remaining lavas has a range of about 10 per cent on either side of that of the average igneous rock.

Alumina is moderate in amount and has a small range. The maximum of 18.2 per cent, which is found in the andesite-basalt of Bill Williams Mountain, is too high, owing to an incomplete separation of magnesia; a value of 17.3 per cent is more nearly correct. Alumina, therefore, in all the lavas except the rhyolites, does not vary more than about 1.5 per cent from the amount found in the average igneous rock and should thus be considered decidedly uniform.

Ferric iron has a rather moderate range, the maximum being about one-third that of igneous rocks whose silica range corresponds to the lavas of the San Franciscan volcanic field. A greater amount than that of the average igneous rock is found only in the andesite-basalts and basalts. For the rest of the lavas the percentage is generally less than 3, the minimum being reached in the rhyolites.

Ferrous iron has a considerably greater range than ferric iron, the maximum being equal to half that for igneous rocks of similar silica range. As in the ferric iron, a greater amount than that of the average igneous rock is found in the more basic lavas, the andesites and basalts, whereas in most of the other rocks it is less than 3 per cent, reaching a minimum in the rhyolites.

Magnesia has about the same range as ferrous iron, but the maximum is less than one-quarter of that of igneous rocks of corresponding silica range. A greater amount than that of the average igneous rock occurs in only five lavas—the most basic ones, Nos. 19 to 23. The value in the other 18 lavas is less than 3 per cent and in 12 of these it is less than 1.5 per cent, so that it is generally rather low.

Lime has a greater range than any of the oxides except silica, and its maximum likewise approaches more closely that of igneous rocks of similar silica range. It has about an equal range both above and below the value in the average igneous rock. The maximum is found in the andesites and basalts and the amounts in the rest of the lavas are less than 5 per cent, the minimum being reached in the rhyolite of San Francisco Mountain.

Soda has the smallest range of the eight principal oxides. The minimum is greater than that of any of the oxides except silica and alumina, though the maximum is about one-half that found in igneous rocks of corresponding silica range. Only in the basalts is the percentage noticeably less than in the average igneous rock, and of the other 21 lavas, 18 have amounts of 4 per cent or more, the maximum being reached in the soda rhyolite of San Francisco Mountain. In rocks of this region, therefore, soda is above the average.

Potash has a fairly narrow range, the maximum being about one-third that of igneous rocks of corresponding silica range. An amount less than that of the average igneous rock is found in 11 out of the 23 analyzed lavas of the San Franciscan volcanic field, and in 10 the amount is higher. Noticeably higher values occur only in the rhyolites.

Titania, phosphoric pentoxide, and manganous oxide are present in small amounts, and their range, as compared with that of igneous rocks of similar silica range and the percentage in the average igneous rock, may be seen by referring to the table.

As the lavas of the San Franciscan volcanic field belong to the commonest rock types it is probable that the ranges of the oxides are of a magnitude that would include the great majority of igneous rocks. From the relative number of igneous rocks in general that fall within the silica range of the lavas of the San Franciscan field it may be estimated that the amounts of the other oxides in possibly 90 per cent of all igneous rocks would fall within the limits shown by these lavas.

SERIAL CHEMICAL CHARACTERS.

METHOD OF REPRESENTATION.

The serial chemical characters of the lavas of the San Franciscan volcanic field are expressed by the relative changes in the amounts of the several oxides referred to silica (fig. 28). This method of representation, though largely one of convenience, does in general refer the bases

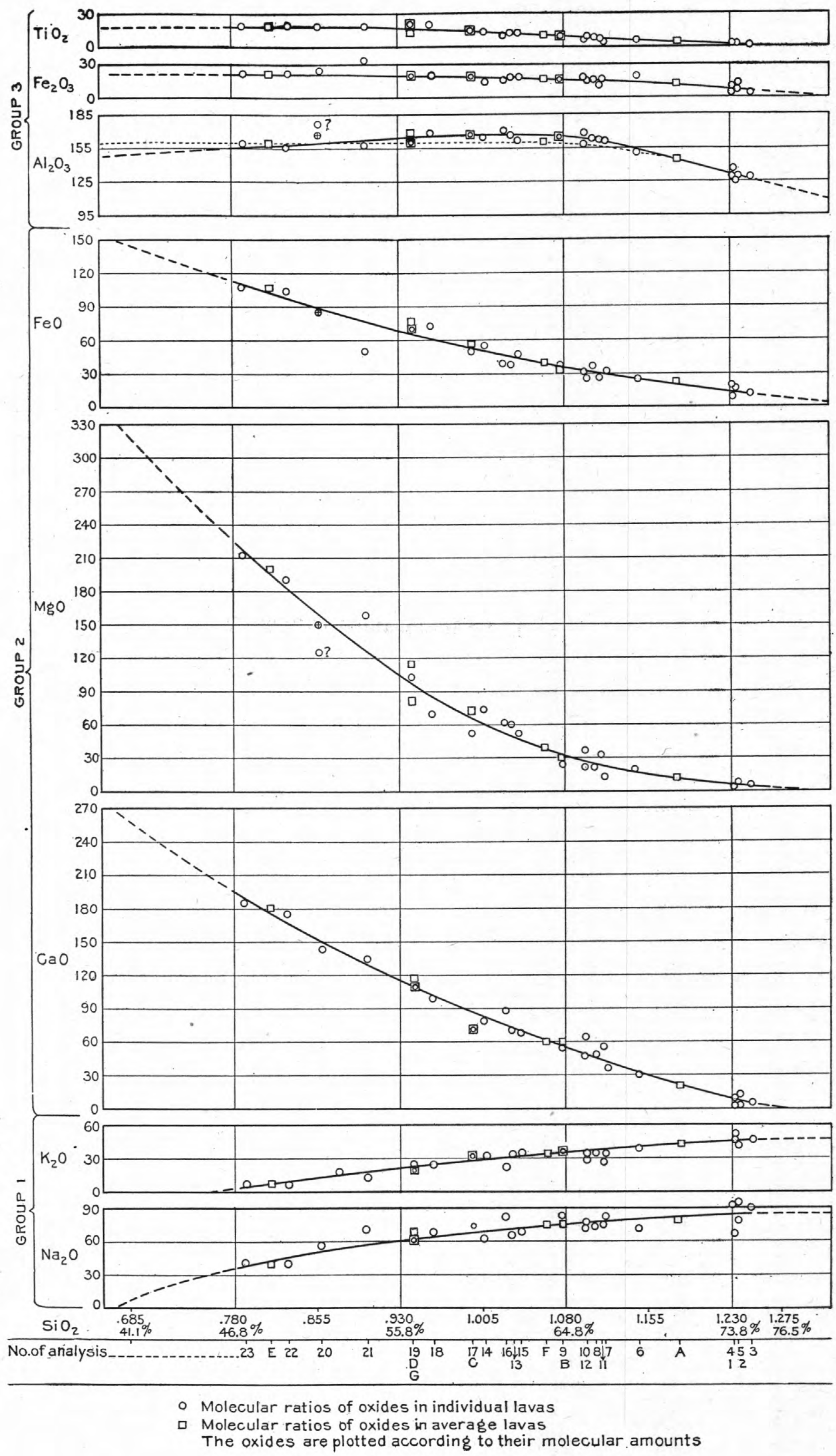


FIGURE 28.—Serial chemical characters of lavas of the San Franciscan volcanic field.

to the principal and practically the only acid radical, thus bringing out the changes that occur in the composition of the rocks from a chemical standpoint.

The curves have been fitted on the assumption that all observations are of equal weight, except a few which will be referred to later. The oxides of the calculated average lavas, which are weighted results, are also plotted. They fit the curves, on the whole, very closely and thus emphasize the continuity of the series. The general accuracy of the curves may be checked by the fact that the sum of the abscissas and ordinates must equal 100. This test for four different silica percentages has been applied with the following results:

Test for accuracy of curves showing serial chemical characters.

Silica	46.8	55.8	64.8	73.8
Other oxides	51.4	42.7	34.5	25.7
Minor oxides not plotted on chart	1.1	1.0	.9	.3
	99.3	99.5	100.2	99.8

The summations are all within the limits of reasonable error and the correctness of the curves as drawn is thus established.

CHANGES IN THE INDIVIDUAL OXIDES.

Alkalies.—Soda and potash increase continuously and gradually in amount as silica increases. The relative increase in the two oxides is almost identical, as shown by the parallelism of the curves, except that it is slightly more rapid for soda when silica is low. The alkali curves gradually flatten as silica becomes high, and become horizontal if continued beyond the actual series. This position would be maintained through a considerable range in silica unless a marked change occurred in the direction of the curves. The alkalies are thus at maximum when silica is somewhat above the highest observed amounts. If the curves are continued beyond the actual series at its lower end it is seen that potash becomes zero at about 45 per cent of silica and soda at 40 per cent. It may be said, therefore, that soda and potash would be lacking in a rock belonging to the San Franciscan sequence which contained less than 40 per cent of silica, whereas they would be at a maximum in one containing from 75 to 80 per cent of silica.

The largest departures of percentages of soda from the curve are found in Nos. 1, 16, and 21; of potash in Nos. 11 and 16. In No. 16 soda is high and potash low, which presumably indicates an analytical error. An excess of not over 0.3 per cent in soda would account for the observed discrepancies. Soda is, however, undoubtedly above the average in No. 16, and this point and the others above noted are considered later in the discussion of the alkali ratios (p. 187).

Lime.—Lime decreases continuously and with gradually lessening rapidity as silica increases. It becomes zero at about 76 per cent of silica. Beyond the lower limit of the series it increases in amount for some distance, possibly as far as is indicated on the diagram. The extrapolation of the curve for lime, as well as the similar curves for magnesia and ferrous iron, can not be successfully accomplished below 40 per cent of silica with the data furnished by the lavas of the San Franciscan volcanic field. The probable character of the curves for these three oxides will be considered in a later paragraph (p. 184).

The percentages depart farthest from the average in Nos. 11, 12, 16, and 17. The high lime in the first three lavas, which are found at Mormon and Bill Williams Mountains, expresses a feature of the regional differentiation of the magma; the low lime of No. 17, the latite of San Francisco Mountain, is probably similarly explained, although in the diagram this peculiarity is not evident in the other lavas of this cone.

Magnesia.—Magnesia decreases continuously in amount as silica increases. The fall is much greater than that for any of the other oxides for low silica, but about equal to that for ferrous iron and less than that for lime for high silica. Zero is reached at about 77 per cent of silica. Beyond the lower limit of the series a maximum of about 13 per cent is reached at 40 per cent of silica.

The wide departure in No. 20, the andesite-basalt of Bill Williams Mountain, is undoubtedly due to an analytical error, as the alumina is correspondingly high. A change of 1 per cent in each gives departures of about average magnitude, and these adjusted values of 6 per cent for magnesia and 17.2 per cent for alumina have been used in calculating the composition of the average lavas. The percentages of these two oxides in the rest of the analyses show no such divergences, so that it is safe to assume that the separations of alumina and magnesia in general were complete within the ordinary limits of analytical error. The discrepancy in No. 21 is due to the rock being an abnormal member of the series.

Ferrous iron.—Ferrous iron also decreases continuously as silica increases. The fall is greatest when silica is low and is throughout less than for either magnesia or lime. If the curve is continued beyond the upper limit of the series zero is reached at 80 per cent of silica, whereas in the opposite direction it rises to a maximum for a low amount of silica. It probably rises about as drawn as far as 40 per cent of silica. The only noticeable departure is in No. 21, for which ferrous iron is decidedly low, whereas ferric iron is high. These amounts are found in the hornblende andesite-basalt of Bill Williams Mountain, which is a secretion in the soda dacite, and as the analyzed material was perfectly fresh they represent a different state of oxidation of the iron from that found in the other members of the series.

Alumina.—Alumina increases very gradually in amount up to 60 per cent of silica; it is then constant until 64 per cent of silica is reached, but from that point decreases rapidly, the lowest amounts being associated with the highest silica. Beyond the upper limit of the series it continues to decrease, as it does very gradually also beyond the lower limit of the series. The only noticeable departure is in No. 20, which has been referred to under magnesia.

A number of the lavas of the San Franciscan volcanic field of intermediate composition contain an excess of alumina over what is necessary to satisfy the lime and alkalies in the feldspar ratio of 1 : 1. (See p. 191.) It is this fact, no doubt, that causes the alumina curve to show a maximum at a point—about 62 per cent of silica—intermediate between the two extremes of the series and thus makes it differ from those of the other oxides. It is interesting to note that if alumina is corrected for this excess the amount becomes constant from the lower limit of the series up to 64 per cent of silica, so that the curve takes the same form as those of ferric iron and titania, as is indicated by the dotted line. It appears quite probable from a preliminary study of the lavas of several volcanic fields in the western part of the country (Lassen Peak region, California; Yellowstone National Park; and Crazy Mountains, Montana) that under normal (ordinary) conditions alumina behaves in this manner—that is, it is constant in amount for low silica and decreases as higher silica is reached—in a series of rocks composed of basalts, andesites, rhyolites, and intermediate types.

Ferric iron.—Ferric iron remains constant in amount up to 53 per cent of silica and then decreases at first very gradually and finally more rapidly until the highest silica is reached. It becomes zero at 78 per cent of silica and remains constant at the opposite end of the series at least as far as 40 per cent of silica. It will be recalled that adjusted values for ferric and ferrous iron, obtained from the calculated modes, have been substituted for those determined by chemical analysis on account of the somewhat altered condition of the calfemic minerals in Nos. 1, 9, 10, 11, 17, 20, and 22. The essential correctness of these values is indicated by the closeness with which they fit their respective curves. The only noticeable departure is in No. 21, which has been referred to under ferrous iron.

Titania.—Titania behaves in the same manner as ferric iron; it is constant in amount up to 54 per cent of silica and then decreases to zero at 76 per cent of silica. Beyond the lower end of the series it remains constant as far as 40 per cent of silica.

GROUPING OF OXIDES.

An inspection of the curves shows that the bases fall into three groups depending on their relative strength.

Group 1 consists of the two strongest bases, soda and potash. These two oxides increase from zero at 40 and 45 per cent of silica, respectively, to maximum amounts at 74 per cent of silica. Their curves when continued to still higher silica values become horizontal. The alkalies thus reach a constant and maximum value, which is maintained up to about 80 per cent of silica.

Group 2 is composed of lime, magnesia, and ferrous iron, which are weaker bases than the alkalies. The characteristic of this group is that the oxides decrease continuously from maximum amounts at lowest observed silica to nearly zero at highest silica. If the curves are continued beyond the highest observed amounts of silica it is seen that lime and magnesia soon, and ferrous iron less quickly, become zero. If the curves are carried beyond the lowest observed amounts of silica the oxides are seen to increase in amount; they can not, however, increase indefinitely, for a point would thus be reached where the sum of all the bases plus silica would exceed 100. It is found by trial that the sum exceeds 100 for all values of less than 40 per cent of silica, so that a change in the direction of the curves must occur at that point.

Group 3 consists of alumina, ferric iron, and titania, which are the weakest bases. The common feature of these oxides, broadly stated, is that they are constant in amount over a greater or less range of low silica and decrease toward highest silica. This is strictly true for ferric iron and titania and would apparently also hold for alumina were it not for an excess of this oxide over the amount necessary to satisfy lime and the alkalies in the feldspar ratio of 1:1 in a number of the lavas of intermediate composition.

Alumina, ferric iron, and titania, may be considered as exercising the control over the composition of the minerals that may form. Thus, to speak broadly, ferric iron and titania take ferrous iron to form magnetite and ilmenite. Alumina governs the amount of the feldspars. Where alumina is greater than the alkalies, as in the basic and intermediate members of the series, the excess is satisfied by lime. The control in the rhyolite of San Francisco Mountain is very evident, as it contains an excess of alkalies over alumina, and soda has gone into riebeckite. The bases remaining after the alumina, ferric iron, and titania are satisfied, go into the calfemic silicates, combining with silica generally in a ratio of not more than 1 : 1. The calfemic silicates may thus be considered as absorbing all the excess bases left from the formation of the ore and feldspars, and this is in keeping with the variable composition which they exhibit, depending on the composition of the rock holding them.

EXTRAPOLATION OF THE OXIDE CURVES.

If the curves of the oxides given in figure 28 are continued beyond the highest observed silica, then lime, magnesia, iron, and titania become zero at different points between 76 and 80 per cent of silica. The alkalies, however, are at a constant maximum amount, whereas alumina is decreasing rather rapidly. But at 100 per cent of silica these three oxides must also become zero. Alumina will practically do so if its curve is continued as already drawn. In order that the alkalies become zero they must decrease more rapidly than is indicated by the known portions of their curves. The change in the direction of the curves must occur at about 79 per cent of silica as above that value the sum of silica, alkalies, and alumina exceeds 100 when the alkali curves are continued in the manner indicated by their known portions.

If the curves of the oxides are continued beyond the lowest observed value of silica, the alkalies soon become zero; lime, magnesia, and ferrous iron increase in amount; ferric iron and titania remain constant, and alumina slightly decreases. It is evident, however, that if lime, magnesia, and ferrous iron continue to increase as rapidly as is indicated by their respective curves a point will soon be reached where the sum of all the oxides will exceed 100. This point is found, by trial, to be at about 40 per cent of silica and consequently below this value the curves for these oxides must change their direction.

It appears, therefore, that lime, magnesia, iron, and titania become zero and that the alkali curves radically change their direction between 76 and 80 per cent of silica. An average may be taken at 78 per cent. On the other hand, alkalies become zero at 40 to 45 per cent of silica and the curves for lime, magnesia, alumina, iron, and titania change their direction at 40 per cent. These two values of 78 and 40 per cent of silica are thus critical in character; they mark the limits beyond which the curves for the bases can not be extrapolated from the data furnished by the lavas of the San Franciscan region. At one extreme a rock would consist essentially of silica, alumina, and alkalies; at the other of silica, lime, magnesia, iron, alumina, and titania. The actual chemical composition of these extrapolated end members is as follows:

Chemical composition of extrapolated end members of the San Franciscan sequence of lavas.

	Acidic end member.	Basic end member.
SiO_2	78.0	40.0
Al_2O_3	11.5	14.9
Fe_2O_3	.3	3.4
FeO	.4	10.9
MgO	....	13.6
CaO	....	15.2
Na_2O	5.3	....
K_2O	4.4	....
TiO_2	....	1.5
Other oxides	....	....
	99.9	99.5

Further consideration of these end members is postponed until the serial mineral characters of the lavas are discussed (pp. 197–200).

CONCLUSIONS.

The continuity of the changes in amounts of the oxides is most striking in view of the fact that the chemical analysis of each lava was made on a single fragment representing the merest fraction of the entire rock mass to which it belonged. There is but one analysis which fails to fit completely into the series—No. 21, the hornblende andesite-basalt of Bill Williams Mountain. The failure is, however, only partial and confined to magnesia and ferrous and ferric iron. The sum of the irons is normal, so that some peculiarity in the conditions under which this rock formed caused an oxidation of the iron different from that in the other members of the series. This rock, it will be recalled, is a secretion in the dacites and is variable in composition. It is not improbable, therefore, that a composite analysis of it would fit throughout.

The serial chemical characters strongly support the inference that the lavas of the San Franciscan volcanic field are all genetically related and are the differentiation products of a homogeneous magma from which they have been derived according to some law. The only law or laws which appear sufficiently comprehensive to explain the observed phenomenon are those of chemical solution. As will appear later, the serial mineral characters, the specific gravities, and the textures of the lavas furnish similar evidence and should be considered, it is believed, as raising this inference to the rank of a definite conclusion. The matter is, of course, not susceptible of direct proof, but the accumulative indirect evidence carries great weight.

RATIO OF ALUMINA TO LIME AND ALKALIES.

The ratio of alumina to lime and alkalies is of interest, as these oxides, with silica, form the feldspars. It is represented graphically by figure 29, *A*. The oxides are expressed in molecules, the amounts being the averages given by the curves in figure 28 for 15 different amounts of silica. The dotted line *a–b* is the ratio of 1:1, in which, theoretically, alumina combines with lime and alkalies to form the feldspars. The distinct maximum in the curve at 176 molecules of lime and alkalies is caused by alumina reaching a maximum at that point, as appears in figure 28, beyond which it is nearly constant in amount, the range being 10 molecules—from 156 to 166.

Alumina and lime plus alkalies, as is shown by the curve, are present in nearly the feldspar ratio of 1:1 up to a lime-alkali amount of 170 molecules, but from that point on lime and alkalies become increasingly greater in amount than alumina. This latter feature is caused by the marked increase in lime which occurs in the more basic rocks. The 1:1 ratio is evident between the lime-alkali amounts of 133 and 170 molecules, because these oxides are almost entirely in the feldspars. Alumina is, however, less than lime and alkalies for amounts of the latter between 133 and 147 molecules and greater between 147 and 164 molecules, as shown by the curve lying to the right and left, respectively, of the straight line indicating the 1:1 ratio. The deficiency in alumina occurs in the rhyolites and is clearly evident from the presence of the iron-soda amphibole, riebeckite. The excess is found in a number of the dacites and latites, but is not microscopically evident. It is, nevertheless, a real excess which is most probably held by the alkali feldspars instead of separating out as corundum. It will be further considered in discussing the mineral character of the lavas (pp. 191–192).

A preliminary study of the ratios of alumina to lime and alkalies in the lavas of the Yellowstone National Park, the Crazy Mountains, and the Crater Lake and Lassen Peak regions, which have a general similarity in composition to the lavas of the San Franciscan volcanic field shows that this excess of alumina over lime and alkalies may be a rather common feature in rocks of acidic composition, such as rhyolites and dacites. The correctness of this view is further supported by the presence of small quantities of "corundum" in the norms of many of the rocks in orders 1 to 4 of Class I of the quantitative system of classification.

The curve for the ratio of alumina to lime and alkalies in the type rocks of the basalt-andesite-rhyolite series, which are given in the preceding chapter (pp. 99–103), is presented for comparison in figure 29, *B*. The general resemblance between the curve of the San Franciscan sequence of lavas and that of the type series is evident. As would be expected, however, the excess of alumina is absent in the type curve and this results in the somewhat flatter form of the curve and the nearer approach to horizontality at its extremity. The lavas of the San Franciscan volcanic field are therefore characterized by an excess of alumina over lime and alkalies in the latites and dacites and a deficiency in the rhyolites.

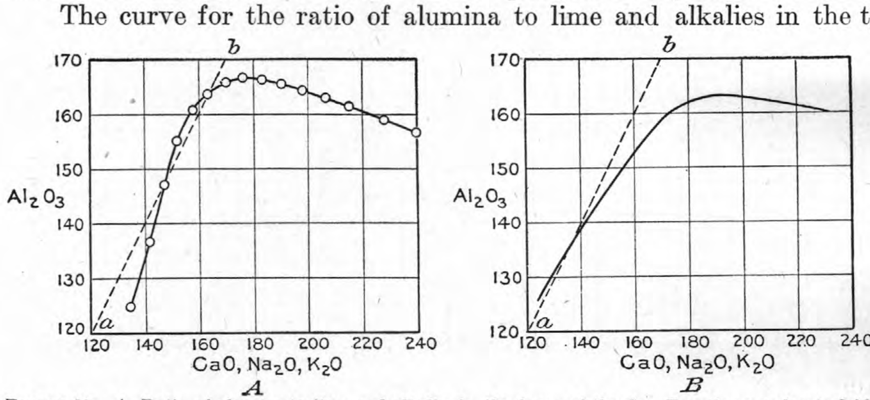


FIGURE 29.—*A*, Ratio of alumina to lime and alkalies in the lavas of the San Franciscan volcanic field; *B*, Same ratio in type rocks of basalt, andesite, and rhyolite series.

RATIO OF THE ALKALIES.

A study of the alkali ratios of the individual lavas (fig. 30) shows that those of the lavas of the composite cones of the second period of eruption tend to group themselves either entirely above or below the average ratio curve and also that there are several marked departures from the average. The curve (X–Y), indicating the average ratio, is plotted from values of potash and soda taken from their curves as drawn in figure 28 and not from the individual ratios themselves. The latter should be evenly distributed either side of the curve, as they have equal weight, except Nos. 16 and 21, which have been disregarded for reasons already stated. This is the actual condition, for 8 ratios are above, 8 below, and 3 on the average, thus showing that the alkali curves in figure 28 have been correctly drawn.

The ratio of the alkalies in the rhyolite of Sugarloaf Hill (No. 1) is far below the average, owing to high potash as compared with the other lavas of this group. The ratio in the soda rhyolite of San Francisco Mountain (Nos. 4–5), on the contrary, varies in the opposite direction, whereas that of the Marble Hill rock (No. 2) is close to the average. The weighted ratio for these three rocks, it will be noted, is very near the average at *m*. It seems permissible, as these three rocks were erupted at closely adjacent vents, to consider them parts of a single body of magma in which the alkalies underwent complementary differentiation, giving rise to the potash-rich lava of Sugarloaf Hill, the soda-rich lava of San Francisco Mountain, and the normal rock of Marble Hill.

The ratios for the two lavas of Mormon Mountain (Nos. 11 and 16) lie well above the curve on account of low potash. Even with allowance made for the probable error in the determination of the relative amounts of the alkalies in No. 16 the ratios depart farther from the average than those of the similar lavas of the other composite cones and suggest that Mormon Mountain, which occupies an isolated position on the Black Mesa, 28 miles from the nearest large cone of the main group, should be considered as a more or less independent seat of eruption.

The alkali ratio of the hornblende andesite-basalt of Bill Williams Mountain (No. 21) is far above the average, owing particularly to high soda. This is significant of the fact that this rock is the most abnormal member of the series in the San Franciscan field. It occurs as a secretion in the dacites and has their soda-rich character and mineral composition, having hornblende as the only calfemic silicate, whereas the andesites and basalts have normal alkali ratios and contain augite and olivine.

Of the five lavas of San Francisco Mountain four, Nos. 4–5, 9, 17, and 18, have ratios above the average and one, No. 8, is slightly below. The ratio of the average lava of this cone, $K_2O : Na_2O :: 33 : 76$, is above the average. The lavas are thus relatively rich in soda for the amount of potash which they contain.

Of the four lavas of Kendrick Peak three, Nos. 6, 13, and 14, have alkali ratios below, and one, No. 19, is on the average. The ratio of the average lava, $K_2O : Na_2O :: 38 : 69$, is well below the average. These lavas are thus relatively poor in soda for the amount of potash they contain.

Of the alkali ratios in the two lavas of O'Leary Peak one (No. 7) is above and the other (No. 15) is below the average. The amount of potash is the same in both lavas so that the difference is due entirely to soda. The average ratio falls exactly on the curve. If the lavas are considered parts of a single body of magma, soda is then present in them in complementary amounts.

The ratio of the dacite of Bill Williams Mountain, No. 12, is above, and that of the andesite basalt, No. 20, is on the average. The average lava of this cone thus has a ratio slightly above the average and is relatively rich in soda for the amount of potash it contains.

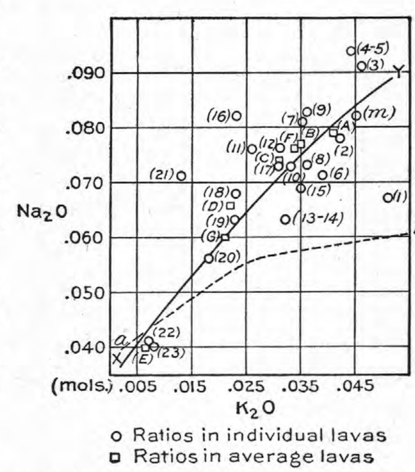


FIGURE 30.—Ratio of alkalies in the lavas of the San Franciscan volcanic field.

It is thus seen that the lavas of San Francisco, Bill Williams, and Mormon mountains have alkali ratios, on the whole, above the average and are relatively rich in soda for the amount of potash they contain. The lavas of Kendrick Peak, on the contrary, have ratios below the average and are relatively poor in soda; of the ratios of the two lavas of O'Leary Peak one is above and the other below the average. This grouping of the lavas is an expression of the regional differentiation of the magma, which has been described in a preceding section (pp. 185 et seq.).

Taking the ratios as a whole, it is seen (fig. 30) that they lie above the curve *a–b* of the alkali ratios for the type series of basalts, andesites, and rhyolites. The only exceptions are in the basalts, Nos. 22 and 23. The alkali ratio in these lavas conforms to the type. With increasing acidity in the composition of the lavas the divergence between the average ratio of the San Franciscan sequence and that of the type series becomes more marked until a maximum is reached in the rhyolites. This clearly brings out the soda-rich character of the lavas of the San Franciscan field (except the basalts), as compared with the types, which is, indeed, their most distinctive chemical feature.

SUMMARY OF THE CHEMICAL CHARACTERS OF THE LAVAS.

As compared with the reference types, the amounts of the several oxides are such as in general place the lavas of the San Franciscan field in the following groups:

1. Normal basalts and andesites, although the former are marked by slightly high magnesia and lime and the latter by slightly high soda.
2. Normal latites.
3. Dacites, on the whole, rich in soda and slightly poor in potash. Magnesia and lime are below the average, whereas ferrous and ferric iron are normal in amount. Most of the members of this group are also marked by an excess of alumina over the amount necessary to satisfy lime and alkalies in the feldspar ratio of 1 : 1, as well as the small amount in the calfemic silicates.
4. Rhyolites distinctly rich in soda and poor in potash; other oxides present in about normal amounts. In those of San Francisco Mountain and Sitgreaves Peak alkalies are in excess of alumina, and soda has combined with ferric iron to form riebeckite.

The most distinctive feature of the lavas as a whole is their richness in soda and poorness in potash as compared with the corresponding types, which becomes increasingly marked from the andesites through the rhyolites.

MINERAL CHARACTERS.

OUTLINE OF DISCUSSION.

The modes of the lavas of the San Franciscan volcanic field, considered as holocrystalline rocks, are assembled in the accompanying table in the same order as the chemical analyses in the table previously given (p. 178). The arrangement is in general, therefore, from the most salic to the least salic members. It thus illustrates the character and extent of the mineralogic changes that occur with changing chemical composition.

Modes of the lavas of the San Franciscan volcanic field.

Individual lavas.

No.	Quartz.	Orthoclase.	Albite.	Ab_4An_1.	Ab_5An_3.	Ab_4An_3.	Ab_5An_4.	Ab_1An_1.	Ab_4An_5.	Ab_7An_9.	Ab_3An_4.	Ab_2An_3.	Excess alumina	Biotite.	Riebeckite.	Hornblende.	Hypersthene.	Augite.	Olivine.	Magnetite.	Apatite.	H_2O.	Sum.	Sp. gr.
1	30.1	29.3	33.0	4.0										1.1						0.6		1.8	99.9	2.58
2	29.5	21.8	36.1			8.4								3.1						.9			99.8	2.64
3	26.9	25.6	39.2	4.0											4.2							.3	100.2	2.63
4	24.5	25.6	43.0												6.9							.2	100.2	2.65
5	25.4	23.4	44.0												7.0								99.8	2.67
6	25.1	19.5	24.7		20.0								0.9	4.5		1.0				3.2	0.3	.8	100.0	2.71
7	21.2	16.7	27.5		23.8								.9	5.4						3.6	.3	.5	99.9	2.72
8	20.0	18.9	18.3		30.4								1.1	2.5		2.5	1.7			3.7	.3	.3	99.7	2.78
9	13.2	20.0	31.3					24.4									3.7	1.1		4.5	.3	.3	99.8[a]	2.74
10	21.2	18.4	28.3					20.0					2.5			2.0	2.4			4.2	.7	.4	100.1	2.78
11	22.0	14.5	31.5						17.5				2.0			8.0	.9			1.9	.3	1.6	100.2	2.76
12	18.7	16.2	26.3					26.2						1.9		6.2	.9			3.1	.4	.6	100.5	2.75
13	16.0	18.4	18.0				28.0						1.6				5.3	5.0		5.2	.5	.8	99.6	2.82
14	12.8	17.8	20.5								26.8		1.6				9.4	5.0		4.4	.5	.8	99.6	2.86
15	13.2	19.5	24.7						25.6							7.0	4.3			5.2	.3	.5	100.3	2.83
16	10.4	12.8	25.5					35.0								2.0	5.4	3.7		4.4	.6	.6	100.4	2.81
17	11.2	17.5	27.6						21.6				1.4			10.8	3.0			5.3	.8	.8	100.0	2.86
18	10.1	13.1	20.7							34.1							3.6	8.0	2.4	6.9	1.0	.1	100.0	2.92
19	8.6	12.8	18.6							32.8							5.5	9.3	4.3	6.5	.7	.5	99.6	2.92
20	2.6	10.0	11.5									44.5					6.7	11.0	5.0	7.6	1.0	.5	100.4	3.02
21	7.1	4.4	23.8								14.2					47.6				2.0	.3	1.3	100.7	2.99
22		1.2									47.1						8.0	16.1	13.2	7.3			99.9[b]	3.06
23		1.1									51.2						10.0	20.2	9.2	6.6	1.1	.2	99.6	3.09

Average lavas.

No.	Quartz.	Orthoclase.	Albite.	Ab_4An_1.	Ab_5An_3.	Ab_4An_3.	Ab_5An_4.	Ab_1An_1.	Ab_4An_5.	Ab_7An_9.	Ab_3An_4.	Ab_2An_3.	Excess alumina	Biotite.	Riebeckite.	Hornblende.	Hypersthene.	Augite.	Olivine.	Magnetite.	Apatite.	H_2O.	Sum.	Sp. gr.
A	25.6	20.0	33.0		13.4									5.0						2.4	0.2	0.5	100.1	2.68
B	16.0	19.5	29.8					21.2					0.8			7.0	1.0			4.3	.4	.3	100.3	2.78
C	10.2	17.2	28.6						21.6				1.3			12.0	3.0			4.9	.7	.7	100.2	2.85
D	7.1	12.2	19.9							33.6							4.0	13.0	2.5	6.5	.7	.2	99.7	2.92
E		1.0									51.2						10.0	19.7	10.0	7.0	1.0		99.9	3.07
F	15.4	18.9	29.3					20.0					.9			8.5	1.5			4.2	.7	.6	100.0	2.78
G	8.4	11.7	16.1							35.0							3.5	14.0	5.0	5.1	.7	.4	99.9	2.92

[a] Including 0.5 per cent garnet.

[b] Including 4.1 per cent calcite and 3.1 per cent unidentified minerals.

It will be recalled, however, that the modes have been calculated from the chemical analyses, so that it is not permissible to correlate the modes and the chemical composition of the lavas unless it can be shown that the former represent what would be the actual mineral composition of the rocks were they holocrystalline. So far as the character of the component minerals is concerned the calculated modes agree with the actual modes, for the minerals have been determined by a study of the rocks in thin section. The question to decide is how nearly the calculated amounts of these minerals agree with the actual amounts. On this point there is the certain evidence that the calculated and micrometrically determined modes of the holocrystalline granite porphyry (No. 5) and the two basalts (Nos. 22 and 23) are essentially identical. In several other lavas (Nos. 8, 9, 10, 11, 12, and 18) the measured calfemic minerals on the average represent 87 per cent of the calculated amount. A study of the thin sections of these lavas shows that a certain proportion of the calfemic minerals is in the groundmass, and it is a reasonable conclusion that if the crystals were all of measurable size—over 0.01 millimeter—the agreement would be more exact. In lavas Nos. 6, 10, 11, 14, and 18 the measured plagioclase tends to equal the calculated amount, although to consider this a true agreement necessitates the assumption that the plagioclase has mostly crystallized in measurable crystals—that is, it occurs as phenocrysts. In lava No. 21, also, there is a very good agreement between the hornblende, which has entirely crystallized, and the plagioclase, which has probably largely done so in the micrometric analysis and the calculated mode. Thus, wherever the test may be made, the agreement between calculated and measured amounts of the minerals is close enough to warrant the general assumption that the calculated modes correctly represent what would be the actual modes if the rocks were holocrystalline. It may be concluded, therefore, that the modes have a value independent of the chemical composition, and hence that it is valid to correlate the mineral composition and chemical composition of the lavas.

GENERAL CHARACTERS.

Broadly speaking, as the chemical composition of the rocks becomes more basic, quartz, orthoclase, and albite decrease in amount, the plagioclase increases both in amount and in basicity, and all the calfemic minerals occur in increasing quantity. This is the equivalent mineral expression of the general changes that take place in the relative amounts of the several oxides, as described under the serial chemical changes.

Quartz occurs in all the lavas except the basalts and ranges from 30 per cent in the rhyolites to about 3 per cent in the andesite-basalt of Bill Williams Mountain. Orthoclase is found in all the lavas, though in very small amount in the basalts. Its range, in round numbers, is from 1 to 28 per cent, or about the same as that of quartz. The potash in the basalts is sufficient to form a larger amount of orthoclase, but the maximum possible quantity is reduced about 75 per cent by the inclusion of potash in the plagioclase. Albite is present in all the lavas except the basalts and ranges in amount from 11.5 to 44 per cent, the latter being found in the riebeckite-soda granite porphyry of San Francisco Mountain. The percentages for orthoclase and albite simply represent the amounts in which the two minerals may individually crystallize. Actually they may be combined in soda orthoclase or intergrown as microperthite, but this unfortunately has to be disregarded, as it is not possible to determine the extent of these modes of occurrence. The sum of quartz, orthoclase, and albite ranges from 25 to 95 per cent, and in all but one mode (No. 20) exceeds, as a rule greatly, the amount of plagioclase in the rock.

The plagioclase occurs in nine different varieties, ranging from Ab_4An_1 to Ab_2An_3—acidic oligoclase to labradorite. In a broad way the plagioclase becomes more basic and increases in amount with increasing basicity of the rock, although with some minor irregularities. These may be due partly to an unavoidable error, namely, the assignment of an improper average composition to the plagioclase, because of the lack of sufficient correctly cut crystals on which to make accurate determinations, or to variation in the composition of the plagioclase itself. Two particular instances of a considerable actual variation in the composition of the plagioclase in lavas of practically identical chemical composition may be cited. The couples are Nos. 8 and 9, of San Francisco Mountain, and Nos. 13 and 14, of Kendrick Peak. The lavas of each couple are very closely related and belong to successive eruptive stages. In No. 8 the composition is Ab_5An_3 and in No. 9 it is Ab_1An_1, although the difference in lime in the two lavas is but 0.3 per cent and soda is greater in No. 9. In No. 13 the composition is Ab_5An_4 and in No. 14 it is Ab_3An_4, with a difference in lime of 0.45 per cent and in soda of 0.15 per cent. In each of these pairs one lava contains a plagioclase more acidic and the other lava one more basic than is normally the case in similar lavas at other localities in the region. As the differences in the amounts of lime and soda are not sufficient to account for this variation in the composition of the plagioclase, it must evidently be due to changes in the physical conditions under which the lavas were erupted. This peculiarity in the composition of the plagioclase in the lavas of both San Francisco Mountain and Kendrick Peak is additional evidence that a very close relation exists between these two cones and is confirmatory of the general relationship of the cones of the second period of eruption.

The extreme values for plagioclase are zero in the soda rhyolite of San Francisco Mountain and 50 per cent in the basalts, the range being the greatest among the minerals that occur in the lavas of the San Franciscan volcanic field. A very notable exception as to the amount of plagioclase, although not with respect to its composition, is found in the hornblende andesite-basalt (No. 21) of Bill Williams Mountain, which will be referred to later.

A small excess of alumina appears in several modes. It represents the amount which could not be utilized in the formation of any of the known minerals of these lavas and occurs principally in the dacites. In the modes Nos. 6, 7, 8, 10, and 11 there is a molecular excess of alumina over the sum of lime, soda, and potash. In Nos. 13, 14, and 17 there is a deficiency, and the final excess is due to lime going into pyroxene or hornblende instead of feldspar. In Nos. 9, 12, 15, and 16 the deficiency of alumina with respect to lime and alkalies is so great that no excess results even after lime has gone into the calfemic minerals. The amount of this unsatisfied alumina is small, the average value being 1.7 per cent.

There is no doubt of the reality of this excess of alumina over the amount necessary to satisfy lime and alkalies in the formation of the feldspars according to the ratio of 1:1 and that which goes into the calfemic minerals. The only question is as to its mode of occurrence. The evidence seems clear that it does not occur as corundum, but forms a solid solution, most probably with the soda feldspars. Morozewicz [1] has observed that alumino-silicates rich in soda dissolve alumina much more freely than potash compounds, and the lavas of the San Franciscan field are to a certain extent rich in soda.

A study of feldspar analyses shows that a majority of them have an excess of alumina over the 1:1 ratio. Thus 37 out of 47, or 79 per cent, of the analyses of albite and anorthoclase in Dana's Mineralogy [2] and Rosenbusch's Elemente der Gesteinslehre [3] show an excess of alumina and ferric iron over lime and alkalies. On the other hand, but 11 out of 20, or 55 per cent, of the orthoclase analyses [4] show this excess. The much larger proportion of albite and anorthoclase as compared with the proportion of orthoclase that shows excess alumina is most suggestive. It can not be due to analytical errors, although the quality of a number of the analyses is not good, because the same determinations are common to all three minerals. A similar excess of alumina is seen in the soda feldspars from Pantelleria, of which 11 analyses are given in Dana's Mineralogy. In the modes of the rocks of the San Franciscan region this small amount of alumina is considered simply as an unsatisfied excess, although it would be proper to put it in albite or, apparently, in the plagioclase.

This excess of alumina in the rocks of the San Franciscan field is also brought out by the ratio of alumina, corrected for the amounts in the calfemic silicates, to the lime and alkalies in

[1] Experimentelle Untersuchungen über die Bildung der Minerale im Magma: Min. pet., Mitt., vol. 18, Nos. 1–3, 1898, pp. 1–90, 105–240, 8 plates. Review by J. A. Jagger, jr., Jour. Geology, vol. 7, 1899, p. 300.

[2] Edition of 1892, pp. 319–331. Orthoclase, Nos. 7, 8–9, 10, 17, 18, and 21; microcline, Nos. 13 and 17; orthoclase, Nos. 22 and 23; and anorthoclase, Nos. 1 to 9 (all Pantelleria); anorthoclase, Nos. 10, 11, 13, 15–16, and 17; albite, all except Nos. 2 and 12. A number of analyses are omitted as being of obviously inferior quality or incomplete.

[3] Edition of 1898.

[4] Dana's Mineralogy. Orthoclase, Nos. 1, 2, 3, 5, 6, 11, 13–14, 15, 16, and 19; microcline, Nos. 5, 14, 15–16, 19. The rest of the analyses are from Rosenbusch.

the feldspars. The correction for alumina is obtained from the calculated modes of the lavas. The lime in the feldspars is an average of the amount in the anorthite molecule and of total lime corrected for the quantity in the calfemic minerals. This average is taken because the two methods give slightly different results. The alkalies have likewise been corrected for the small amounts in the calfemic silicates. The final figures are given in the following table and are also expressed graphically in figure 31, where the abscissas represent silica and the ordinates the ratios of alumina to lime and alkalies. The feldspar ratio of 1:1 is indicated by the broken line.

Ratio of alumina to lime and alkalies (referred to silica) in the feldspars of the lavas of the San Franciscan field.

SiO_2.[a]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Al_2O_3	0.146	0.149	0.152	0.154	0.156	0.157	0.159	0.161	0.160	0.158	0.155	0.151	0.143	0.134	0.122
CaO+alkalies	.147	.150	.151	.153	.153	.153	.153	.151	.151	.148	.146	.144	.143	.134	.122
$\frac{Al_2O_3}{CaO+alkalies}$	.99	.99	1.01	1.01	1.02	1.02	1.04	1.07	1.07	1.07	1.06	1.05	1.00	1.00	1.00

[a] Silica ranges from 0.780 molecule (46.8 per cent) to 1.250 molecule (75 per cent), divided into 15 equal parts.

It is seen, in figure 31, that in the basalts and andesites the ratio is as near 1:1 as could be expected in view of the manner in which the corrections have been obtained, and in the rhyolites, where corrections may be more definitely determined, it is exactly 1:1. Between the values of 59 and 71 per cent of silica, however, the ratio rises above unity, and in this part of the series there is an average excess of 8 molecules of alumina over the amount necessary to satisfy lime and alkalies in the feldspar ratio of 1:1. The position of the lavas which show this excess of alumina is indicated in the figure by crosses.

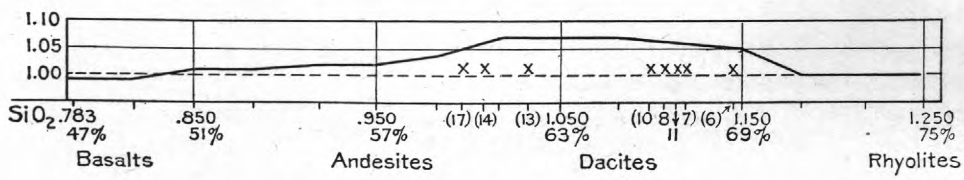


FIGURE 31.—Ratio of alumina to lime and alkalies in the feldspars of the lavas of the San Franciscan field.

It will be observed in the foregoing table that the sum of lime and alkalies in the feldspars is very nearly constant up to an amount of silica represented by No. 10, which is equal to 65 per cent. The range is 6 molecules, or 4 per cent of the average number. The interpretation of this fact appears to be that the amount is controlled by the alumina. As already noted (p. 183), alumina tends to constancy at low silica values in the type basalt-andesite-rhyolite series; the lime and alkalies thus behave in the same manner, although their total amount in this part of the series is greatly in excess of alumina.

A study of the Washington and Washington-Roth tables of analyses shows that a large proportion—about two-thirds—of the norms of rocks falling in Class I, orders 2, 3, and 4, and a small proportion of those in Class II, orders 3 and 4, contain excesses of alumina, which is designated as corundum. The presence of this excess of alumina can not be explained, in general, as resulting from analytical errors or from the method of calculating the norm. It would disappear in some modes having biotite as the chief calfemic silicate, but not in all of them; whereas in those with hornblende or augite the excess would be increased, because these minerals contain much more lime than they do alumina. The excess of alumina, which is observed in the norms and which would still persist in most of the modes, may be explained very simply and in general correctly, it is believed, by the fact here shown that the alkali feldspars, especially the soda-rich varieties, commonly hold a greater amount of alumina than is necessary to satisfy the alkalies in the standard proportion of 1:1.

Among the calfemic minerals the relation that exists between biotite, hornblende, hypersthene, augite, and olivine may first be noted. It will be seen that the presence and amount of these minerals depend to a striking degree on the chemical composition of the rock in which they occur. Broadly speaking, their total amount increases rather uniformly from a minimum in the rhyolites to a maximum in the basalts.

Biotite is practically confined to the rhyolites, with which are included the biotite dacites of Kendrick and O'Leary peaks, because of their similar texture. It is the normal calfemic mineral of the rhyolites, whereas the soda amphiboles (mostly riebeckite) of the rocks of San Francisco Mountain are considered abnormal. Lavas containing riebeckite constitute only about one-third of the total volume of erupted rhyolite and occur, to the exclusion of the normal type, only at San Francisco Mountain.

Hornblende is found in rocks, either dacites or latites, with a silica content of 60 to 66 per cent, and is the dominant normal calfemic mineral in those lavas in which it occurs. A single exception may be noted in No. 21, which contains 47.6 per cent of hornblende with 54 per cent of silica. This rock has very low plagioclase and magnetite, a condition which expresses the fact that the lime and ferric iron have largely gone into the hornblende. The rock is the hornblende andesite-basalt of Bill Williams Mountain, which occurs as a secretion in the dacite of that cone and at other points in the region. Although much more basic than the dacites proper, it does, nevertheless, preserve the mode of that type and consequently has an abnormal mineral composition for an andesite-basalt.

Hypersthene has the widest range of the five minerals under consideration, as it occurs in all the lavas from the dacites to the basalts. Not all of it, however, is in individual crystals. In the basalts, and to a less extent in the andesites, it is combined with augite. In the dacites and latites it crystallizes in characteristic individuals and in Nos. 9, 13, 14 and 16 it is the dominant calfemic mineral.

Augite is found in lavas ranging from the dacites proper, whose silica content is less than 62 per cent, to the basalts, and the amount increases as silica decreases. It is the dominant normal calfemic mineral in the andesites and basalts and, occurring in the more basic lavas, is the most abundant of all the calfemic constituents.

Olivine occurs only in the andesites and basalts whose silica content is less than 58 per cent. It increases irregularly in amount as the rocks become more basic. In the andesites it develops in the presence of quartz, but in the basalts, where the amount is larger, quartz is absent.

Of the remaining calfemic minerals magnetite occurs in all but three of the rocks, Nos. 3, 4, and 5, and increases with considerable regularity from less than 1 per cent in the rhyolites to about 7 per cent in the basalts. Its absence in the rocks noted results from an excess of soda combining with all the iron to form riebeckite. Apatite is found in all the rocks except the rhyolites proper and may occur in them if traces of phosphoric pentoxide are accepted as evidence. It increases in amount with increasing basicity of the rock to a maximum value of 1 per cent in the basalts.

The modes of the lavas, with two exceptions, may be called normal, as they are composed of the minerals most commonly found in rocks of similar character. The exceptions to the rule of normal modes are the hornblende andesite-basalt of Bill Williams Mountain and the riebeckite-soda rhyolite and granite porphyry of San Francisco Mountain. The abnormality of the first rock is very pronounced, in that anorthite and magnetite are much below, whereas calfemic silicates are much above the average. This is the result of hornblende being the only calfemic silicate. If the mode were normal, the amount of the calfemic silicates—hypersthene, augite, and olivine—would be approximately 32 per cent, magnetite 5 per cent, and anorthite 17 per cent.

Discrepancies in two rocks may be mentioned. In No. 20, the augite andesite-basalt of Bill Williams Mountain, the calfemic silicates are low. This is due to an error in the determination of magnesia which was detected in plotting the serial chemical characters. If magnesia is given a value of 6 per cent, which is more in accord with the fact, the calfemic silicates will then equal about 27 per cent and anorthite 23 per cent. This change brings the rock, which is of normal mineral composition, into line with the other members of the series. In No. 16, the latite of Mormon Mountain, albite is high and orthoclase low, which is most likely due to an analytical error in the determination of the relative amounts of soda and potash.

SERIAL MINERAL CHARACTERS.

METHOD OF REPRESENTATION.

The manner in which the amounts of the minerals of the modes vary with changes in the chemical composition of the lavas is graphically represented in figure 32. The modes are

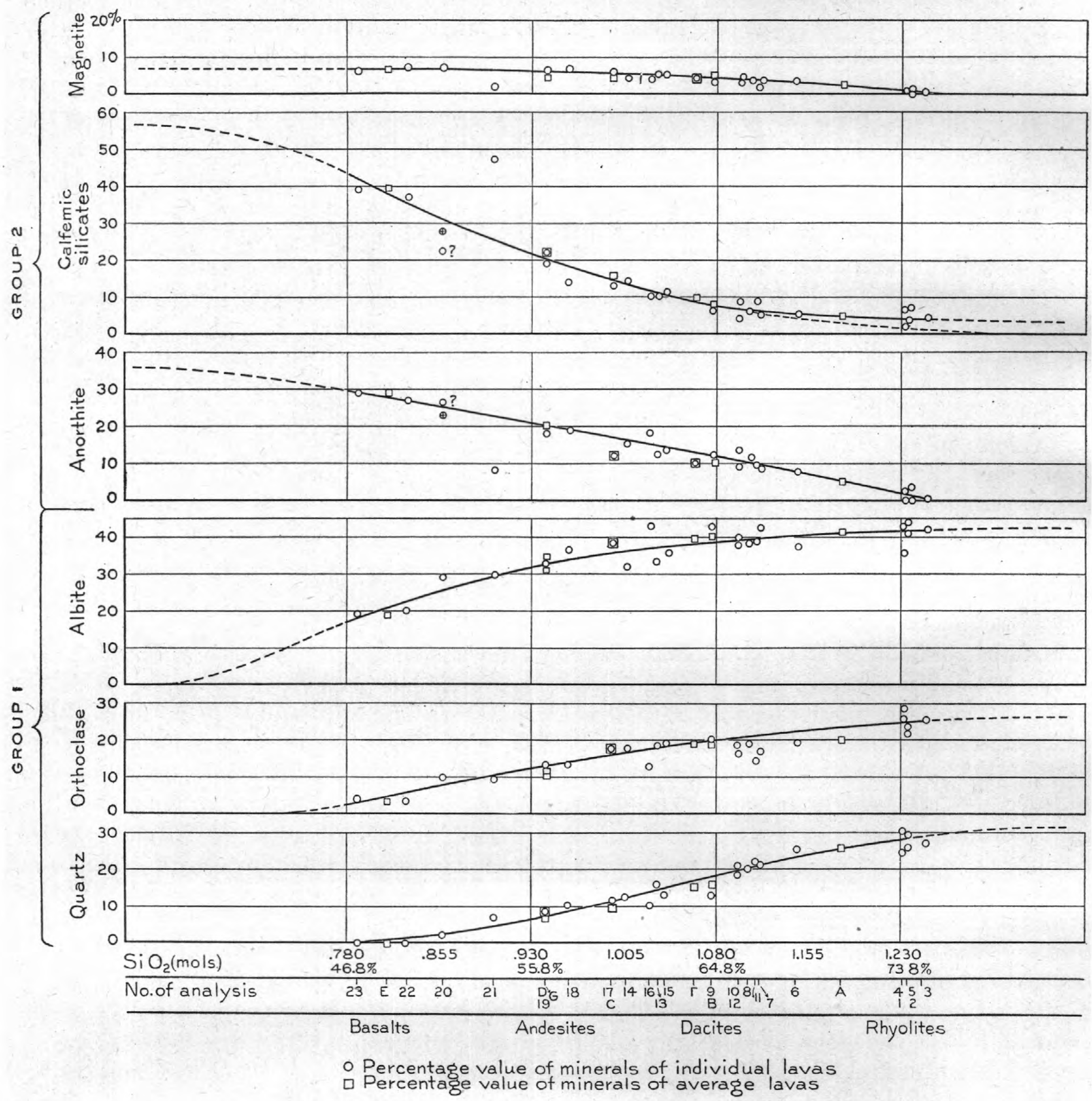


FIGURE 32.—Serial mineral characters of lavas of the San Franciscan volcanic field.

plotted with reference to silica, which has been chosen as the best single independent factor for expressing the general chemical composition of the rocks. In order to represent the modes in this way, it has been necessary to simplify them somewhat. Plagioclase is resolved into its component parts, and the orthoclase and albite, which partly compose it, are included with the independently existing orthoclase and albite. Anorthite is treated separately. It would be more direct to plot the orthoclase and albite of the plagioclase separately from that existing as such, but unfortunately the unavoidable errors in determining the composition of the plagioclase, especially its average composition for the whole rock, are sufficiently great to destroy the significance of these amounts. The calfemic minerals are combined into two groups, one of which consists of the silicates, the other of magnetite and ilmenite. Apatite is omitted because of its very small amount. The calfemic silicates are treated as a sum in order to eliminate minor errors in the determination of their relative amounts. The modes are thus represented by quartz, orthoclase, albite, anorthite, calfemic silicates, and magnetite (including ilmenite), which is as close an approximation to the actual modes as can be satisfactorily made.

The minerals have been plotted according to their percentage values, because this method serves the purpose for which the diagram is intended as well as molecular amounts. The wide range in the latter, from 0 to 30 for magnetite and 0 to 500 for quartz, would make a figure of undue size if a suitable uniform scale were used.

The hypothetical modes of the various average lavas of the region are also plotted on the diagram, the amounts of their minerals being inclosed in squares. It will be seen that they fit the curves with the same degree of closeness as the modes of the individual lavas, which indicates their essential correctness.

An inspection of the curves shows that the amounts of the several minerals possess a noticeably continuous relation throughout the series with the single significant exception of No. 21, the hornblende andesite-basalt of Bill Williams Mountain. The amounts lie particularly close to the curves for quartz, anorthite, calfemic silicates, and magnetite, and slightly less close for orthoclase and albite. A general check is had on the accuracy of the curves, in that the sum of the minerals for any value of silica equals 100. This test has been made with the following results:

Accuracy of curves of serial mineral characters of lavas of the San Franciscan field.

SiO_2	0.780	0.930	1.080	1.230
Quartz	0	6.5	18.3	28.0
Orthoclase	2.2	12.5	20.0	25.0
Albite	17.0	32.0	39.0	41.7
Anorthite	29.5	21.0	12.0	2.0
Calfemic silicates	43.5	21.5	7.5	4.0
Magnetite	7.0	6.0	4.0	1.0
	99.2	99.5	100.8	101.7
Apatite, etc	1.1	.8	.3	....
	100.3	100.3	101.1	101.7

The sums are thus within the limits of error for the lower values of silica and slightly above for the higher values. Apparently the quartz and albite curves have been drawn a trifle too high. A change of 0.5 per cent in each would bring the sums within the limits of error. This is so small that it did not seem advisable to redraw the curves. As a whole, they may be considered essentially correct.

CHANGES IN INDIVIDUAL MINERALS.

Quartz.—Quartz starts at zero in the basalts and increases continuously in amount as the lavas become more acidic in composition. The curve rises less rapidly toward the acidic end of the series, and if continued beyond the rhyolites it becomes horizontal. In this position quartz is consequently constant in amount. This condition is more properly described as the saturation of quartz at the acidic end of the series. The saturation value is 31.5 per cent, and the significant fact is that this is the maximum amount which can enter into any possible member of the San Franciscan sequence of rocks according to the conditions under which the rocks as a whole originated.

Orthoclase.—Orthoclase starts at 4 per cent in the basalts and increases continuously in amount as the lavas become more acidic in composition. The rate of increase, however, is progressively less toward the acidic end of the series, and if the curve is continued beyond the rhyolites it becomes horizontal, as does that of quartz. A saturation value of 26 per cent for orthoclase is thus reached, which can not be exceeded in any possible member of the San Franciscan sequence. In fact, the rhyolites are practically saturated for orthoclase, as the average amount is 25 per cent. An extrapolation of the curve beyond the basic end of the series shows that orthoclase becomes zero in a member which is slightly more basic than the basalts. The amount of orthoclase may be considered as depending almost exactly on the amount of potash in the rock, as all of this oxide, barring trifling quantities in the calfemic minerals, goes into orthoclase.

Albite.—Albite starts at 20 per cent in the basalts and also increases continuously in amount as the lavas become more acidic in composition. The curve rises most rapidly at the basic end of the series and becomes almost horizontal at the acidic end. A saturation point for albite is thus practically reached in the rhyolites. The actual saturation value of 42.5 per cent occurs in a member of the series which is slightly more acidic than the rhyolites, as is true of quartz and orthoclase. By extrapolation of the curve beyond the basalts it is seen that albite does not disappear until a member of the series considerably more basic than the basalts is reached. The curve is slightly flattened toward the end in order to give smoothly flowing curves for the anorthite and calfemic silicates, so that it has somewhat the form of a typical saturation curve. The curve for the actual members of the series, from basalts to rhyolites, is nearly the same as for soda. The rise is, however, slightly greater at the basic end of the series and less at the acidic end, as small but distinctly appreciable amounts of soda enter the augite and hornblende of the more basic rocks and the riebeckite of the rhyolites. The amount of albite depends most closely upon soda, therefore, in the lavas of intermediate composition—the dacites and latites.

Anorthite.—Anorthite starts at 28 per cent in the basalts and decreases continuously until zero is reached in the rhyolites. An extrapolation of the curve beyond the basic end of the series shows that anorthite reaches a saturation value of 36 per cent, the maximum percentage possible in a member of the San Franciscan sequence, slightly below the point where albite becomes zero—that is, in a rock considerably more basic than a basalt. The relation of anorthite to silica is practically a linear one, in which respect it differs from that of lime. Only small amounts of lime enter the calfemic minerals of those lavas whose silica content is between 66 and 75 per cent. For this range, if lime is considered a linear function of silica, the amount of anorthite depends almost directly on the amount of lime. Below 66 per cent of silica, then, lime goes into the calfemic minerals in amounts that cause anorthite to remain a linear function of the entire composition as expressed by silica.

Calfemic silicates.—The calfemic silicates start at 40 per cent in the basalts, and also decrease continuously in amount as the lavas become more acidic in composition. The rate of decrease is most rapid at the basic end of the series and becomes practically zero at the acidic end, where a value of 4 per cent is reached. The calfemic minerals do not become zero because of the presence of riebeckite. In the ideal series this would not occur. Instead, the calfemic silicates would continue to decrease throughout the series until zero was reached in a member slightly more acidic than a rhyolite. The position of the normal curve is indicated on the diagram by a dotted line. By an extrapolation of the curve beyond the basic end of the series it is seen that it gradually reverses its direction and becomes horizontal. A saturation value of 57 per cent for the calfemic silicates is thus reached in a member of the series corresponding in composition to that in which anorthite reaches its saturation value.

Ferrous iron and magnesia enter into the composition of the calfemic minerals throughout the series, whereas lime, in appreciable amounts, enters when the silica content of the rocks is less than 66 per cent. Magnesia is the only oxide which occurs exclusively in the calfemic silicates. In the rhyolites potash plays an important part in the formation of biotite, and soda goes into riebeckite. The character of the curve for calfemic silicates is, in general, the same as that of the curves of ferrous iron, magnesia, and lime. It differs from the curves of these three oxides in that it remains practically horizontal instead of reaching zero at the acidic end of the series.

Magnetite.—Magnetite has a constant value at the basic end of the series and gradually decreases in amount until it reaches zero at the acidic end. The basalts, therefore, are saturated for magnetite. The amount is 7 per cent, which can not be exceeded in any possible member of the San Franciscan sequence of rocks. The curve is essentially the same as for ferric iron and titania, and this is natural, as by far the greater part of these oxides goes into the magnetite. The only divergence is in the rhyolites, where magnetite decreases more rapidly than ferric iron. This is due to the ferric iron combining with soda to form part of the riebeckite molecule instead of forming magnetite with ferrous iron, as throughout the rest of the series.

DISCUSSION OF RESULTS.

DIVISION INTO GROUPS.

An inspection of the curves shows that the minerals may be divided into two distinct groups which, strictly conceived, are mutually exclusive in their limiting positions. At one extreme a rock would be composed only of quartz, orthoclase, and albite; at the other it would consist wholly of anorthite, calfemic silicates, and magnetite. Between these two extremes the groups may be considered as having combined in certain definite proportions to form the lavas of the San Franciscan region. They may apparently combine in all proportions between the two extremes. So far as it goes, the San Franciscan sequence may be considered as representing all possible combinations, as the maximum difference, with one exception, between successive amounts of silica is 2.3 per cent and the average difference is but 1.1 per cent. The antithetic

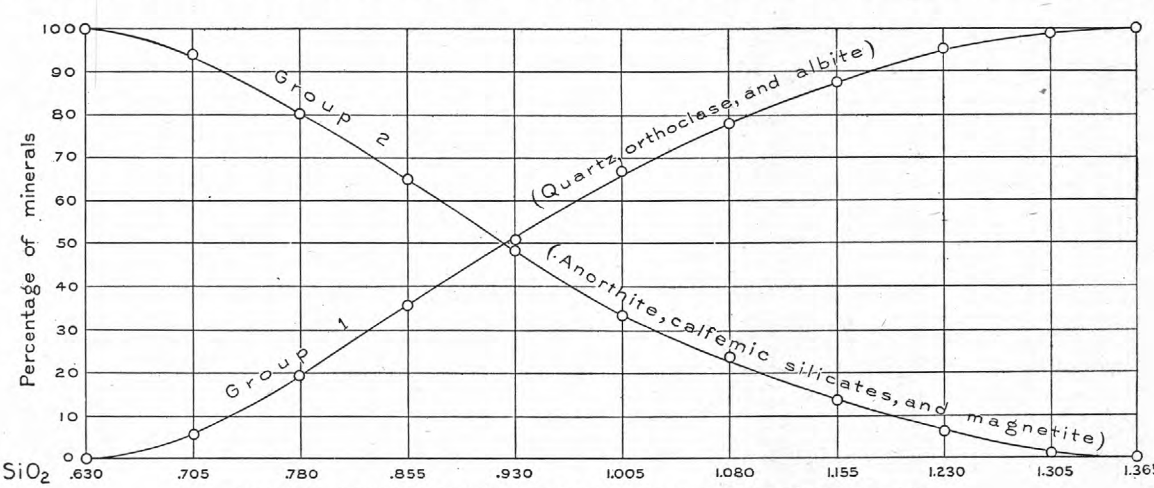


FIGURE 33.—Relation of mineral groups 1 and 2 in the lavas of the San Franciscan field.

character of these two groups of minerals has long been recognized. The interesting and, it is believed, significant fact determined for the rocks of the San Franciscan region is that the minerals of both groups reach saturation points at opposite ends of the series. Fixed limits are thus set to the series, and the composition of the end members may be closely calculated. These features are graphically illustrated by figure 33.

GROUP 1.

Group 1 is composed of quartz, orthoclase, and albite. The characteristic of these minerals is that they start at zero at the basic end of the series and increase to saturation at the acidic end. The form of the curves is such that they may be easily extrapolated and the saturation points thus determined. They are, for the ideal series, as follows:

Saturation points of the minerals of group 1.

Quartz	31.5
Orthoclase	26.0
Albite	42.5
	100.0

The chemical composition, as derived from the above mode, is: SiO_2, 77.5; Al_2O_3, 13.1; Na_2O, 5.0; K_2O, 4.4; total, 100.0. The interesting point is that these values can not be exceeded. Consequently a rock of this composition is the most acidic rock that could have formed in the San Franciscan region under the conditions that gave rise to the rocks as a whole.

Ideal conditions, however, are not exactly realized, for, while anorthite and magnetite disappear, the calfemic silicates remain to the extent of 3 per cent. The limiting acidic member of the series, therefore, actually has the following composition:

Modes of limiting acidic member of San Franciscan sequence and of soda rhyolite of Sitgreaves Peak.

	1	2
Quartz	30.0	26.9
Orthoclase	26.0	25.6
Albite	41.0	42.4
Anorthite		.8
Calfemic minerals	3.0	4.2
	100.0	99.9

1. Mode of limiting acidic member of San Franciscan rock sequence.
2. Mode of soda rhyolite of Sitgreaves Peak.

The rhyolite of Sitgreaves Peak, which is by far the largest mass of rhyolite proper in the region, has essentially the same mode as the acidic saturation member. In general it may be said that the rhyolites of the region are the limiting members of the San Franciscan sequence of lavas at its acidic end.

The chemical composition of the acidic saturation member, as calculated from its mode,[1] is as follows:

Chemical composition of acidic saturation member and of rhyolite of Sitgreaves Peak.

	1	2	3	4
SiO_2	76.5	78.0	77.5	74.9
Al_2O_3	12.8	11.5	13.1	13.1
Fe_2O_3	.7	.3		.5
FeO	.5	.4		.8
MgO	.05			.2
CaO	.05			.3
Na_2O	5.1	5.3	5.0	5.6
K_2O	4.4	4.4	4.4	4.3
TiO_2	.05			.1
	100.15	99.9	100.0	99.8

1. Chemical composition of limiting acidic member of San Franciscan sequence determined from its mode.
2. Same determined from the extrapolated curves of the oxides as given in fig. 28, p. 181.
3. Chemical composition of ideal limiting member as determined from its mode.
4. Chemical composition of soda rhyolite of Sitgreaves Peak.

The agreement between the chemical composition of the acidic end member as determined (*a*) from the mineral composition as fixed by saturation and (*b*) from the extrapolated curves for the oxides (fig. 28), at the point where lime, magnesia, iron, and titania become zero and the curves for the alkalies radically change their direction, is certainly significant. The ideal limiting member is also nearly the same as the actual limiting member; the 3 per cent of calfemic minerals represent an entanglement of group 2 in group 1, which is practically negligible. It may be said, as the composition of the lava of Sitgreaves Peak shows, that the soda rhyolite is the limiting acidic member of the San Franciscan sequence of lavas—that is, it is the most acidic rock that could form under the conditions that gave rise to the sequence as a whole.

GROUP 2.

Group 2 is composed of anorthite, calfemic silicates, and magnetite. The calfemic silicates include biotite, riebeckite, hornblende, hypersthene, augite, and olivine; the magnetite includes ilmenite. The normal characteristic of these minerals is that they start at zero at the acidic end of the series and increase to saturation at the basic end. The extrapolation of the curves

[1] The calfemic silicate is riebeckite. For analysis see p. 114. The quartz, orthoclase, and albite are of standard composition.

for anorthite and calfemic silicates is not quite as simple as for the salic members. The error in the limiting values of these two minerals, however, probably does not exceed 2 or 3 per cent, and a general check is had in that the sum of all must equal 100. The saturation points thus determined are as follows:

Saturation points for the minerals of group 2.

Anorthite	36
Calfemic silicates	57
Magnetite	7
	100

These are, then, the values for the minerals of group 2 which can not be exceeded, and consequently a rock of the above composition would be the most basic possible member of the rock series of the San Franciscan volcanic field.

The detailed mineral composition is somewhat in doubt, owing to difficulty in determining the relative amounts of pyroxene and olivine. It is estimated from the increase of olivine over augite in the basalts as compared with the andesites that the calfemic silicates consist of 39 per cent of augite and 18 per cent of olivine, so that the composition is:

Mineral composition of limiting basic member of rock series of San Franciscan field.

Anorthite	36
Augite	39
Olivine	18
Magnetite	7
	100

The chemical composition of this rock is as follows:

Chemical composition of limiting basic member of rock series of San Franciscan field and average of related rocks.

	1	2	3
SiO_2	41.1	40.0	43.0
Al_2O_3	15.2	14.9	14.1
Fe_2O_3	4.0	3.4	4.7
FeO	9.2	10.9	8.1
MgO	12.6	13.6	11.9
CaO	15.0	15.2	13.8
Na_2O } K_2O	......	......	2.4
TiO_2	2.0	1.5	1.7
	99.1	99.5	99.7

1. Chemical composition of the limiting basic member of the San Franciscan sequence of rocks determined from the mode. Composition of augite used is: SiO_2, 48; Al_2O_3, 5; Fe_2O_3, 2; FeO, 6; MgO, 15; CaO, 20; TiO_2, 2; total, 98.5. Based on analyses Nos. 11, 12, 14, 21, 26, 30, 34, 35, and 40 of augites in basic rocks: Iddings, Rock Minerals, pp. 298–299. Olivine: MgO : FeO :: 3 : 1. Ore consists of 4.5 per cent of magnetite and 2.5 per cent of ilmenite. Anorthite of standard composition.
2. Same determined from the extrapolated curves for the oxides given in fig. 28, p. 181.
3. Average composition of related rocks. Washington table of analyses, p. 328, analysis 3a; 334, 58, 59, and 60; 346, 4 and 6; 358, 7; 362, 2a; 410, 21; 468, 6. Washington-Roth table, p. 60, analysis 1c. Where more than one analysis of the same number occurs on a page, successive analyses after the first are designated by the suffixes a, b, c, etc.

As in the case of the acidic end member, there is a striking agreement between the chemical composition of the basic end member as determined (*a*) from the mineral composition as fixed by saturation and (*b*) from the extrapolated curves for the oxides (fig. 28) at the point where the sum of the abscissas and ordinates begins to exceed 100 and the curves radically change their direction. The agreement is instructive, because it was necessary to estimate both the relative amounts and the composition of the augite and olivine in the mode. It strengthens the belief, derived from calculating the modes of the lavas given in the preceding chapter, that the mineral composition may be successfully calculated from the chemical composition, or vice versa, even when the actual composition of the component minerals is not known.

The lower limiting member of the San Franciscan sequence of lavas is thus an ultrabasic rock belonging to the peridotite group. It is not known to be present in the region; the basalts were the most basic rocks found. The average composition of a number of related rocks is given in column 3 of the table for comparison. This basic end member approaches most closely certain microdiorites and gabbros from the Ural Mountains, Russia, and also a dolerite and limbergite from the Cape Verde Islands. All the related rocks, however, contain appreciable amounts of the alkalies, whereas the basic end member of the San Franciscan region is alkali free. This is because the latter has an ideal composition; it consists wholly of the minerals of group 2. Actually small amounts of the alkalies in some form remain entangled with group 2 in its limiting position, as does a small proportion of group 2 at the limiting position of group 1. As the alkalies are much stronger bases than lime, magnesia, or iron it is generally true that a larger proportion of group 1 remains in group 2 than of group 2 in group 1 in the limiting positions.

SUMMARY.

The minerals of the lavas of the San Franciscan region, in a simplified form, may be divided into two groups, consisting of (1) quartz, orthoclase, and albite, and (2) anorthite, calfemic silicates, and magnetite.

In their limiting positions these two groups are mutually exclusive. In intermediate positions they may be considered as having combined in certain definite proportions to form the lavas of the San Franciscan sequence.

The individual minerals of each group reach saturation at opposite ends of the sequence These saturation points determine the limits of the sequence and make it possible to calculate the composition of the end members. The limit at the acidic end is thus found to be in the soda rhyolites of the region. The lava of limiting basic composition is not represented. It is an ultrabasic rock belonging to the peridotite group.

The mineral groups 1 and 2 (fig. 33) actually become saturated at silica values which are higher and lower, respectively, than those determined from the modes of the limiting members. If silica alone were truly representative of the entire composition of a rock the silica values determined by these two methods should agree, as the mode is an equivalent expression of the chemical composition. The observed discrepancy is due, of course, to the fact that silica is only partly representative of the entire composition. As the results show, however, it is an excellent single factor for expressing the complete chemical or mineral composition of such common rocks as basalts, andesites, rhyolites, and intermediate types. Some of the discrepancy above noted is also due to the approximate manner of calculating the chemical composition of the end members from their modes.

CONCLUSIONS.

The pronounced continuity of the changes in the mineral composition of the lavas of the San Franciscan volcanic field and the saturation of the minerals of groups 1 and 2 at opposite ends of the series should be considered, it is believed, as further proof of a very definite nature that the lavas of the series are genetically related and have been derived from a homogeneous magma. Such continuity can not be thought of as having resulted from chance, as it would be necessary to suppose, for example, if the differences in the composition of the lavas were due to the absorption of foreign material by the magma. On the contrary, the forces which produced the changes in composition must have acted according to definite laws, and the only laws sufficiently comprehensive to explain the observed facts are those of chemical solution.

It would seem to be a reasonable inference, from the serial mineral characters, that the conditions under which the lavas originated and were erupted were highly uniform throughout the period of volcanic activity in the San Franciscan field. This may be considered as due to the location of the field in a region where crustal movements, although extensive, have been of the simplest character and vertical in direction.

The San Franciscan sequence of lavas may be considered as composed of all possible members that could form under the existing conditions except a few which would lie between the basalts and the basic limiting member. If the average silica difference—1.1 per cent—between the known lavas is taken as the measure, there might be six more members to the series. One or two of those nearest the basalts may possibly be present in some of the innumerable basaltic cones. Ultrabasic rocks are in general so much rarer than those lavas actually present in the region that their absence need cause no surprise, especially as abyssal varieties appear more common than lavas. The San Franciscan sequence of lavas may thus be considered nearly complete, and it is also simple. This latter feature, which is due to the uniform magmatic conditions, has no doubt made it possible to express in so definite a manner the relationships here recorded.

The conclusion was reached from the study of the serial chemical characters of the lavas that the curves for the bases could not be extrapolated above 78 per cent (average) or below 40 per cent of silica. It appeared most probable that the curves in general radically changed their direction at about those figures. The first conclusion is verified by the study of the serial mineral characters. The chemical composition of the limiting acidic and basic members of the San Franciscan sequence as determined from the modes shows that these values of 78 and 40 per cent of silica are critical. They are fixed by the saturation points of the minerals of groups 1 and 2 and can not be exceeded.

The two opposing groups of minerals here recognized call to mind the theories of Bunsen [1] and Durocher [2] as to the existence of two primary magmas by mixtures of which all igneous rocks were formed. Two important differences, however, may be noted: (*a*) The interpretation of the groups is strictly mineralogic; (*b*) the groups, in general, do not necessarily have a fixed mineralogic composition. Every group of related rocks (petrographic province) will have its own particular groups of minerals. However, as the rock sequences of many different provinces are of similar character, varying only in minor degree, it will happen that their opposing groups of minerals will consist of the same species with slightly variant composition.

It is to be presumed, if the composition of igneous rocks is governed by the laws of chemical solution, that the two opposing groups of minerals, as here conceived, offer a simple and convenient manner of representing certain facts rather than an indication of the actual process of rock genesis; they should be considered a convenient expression for a complex phenomenon. To what extent truth may be sacrificed to convenience is difficult to say. If the method is largely one of convenience, it may be questioned whether the saturation of the minerals of the two groups in their limiting positions has real significance. This would be the more true if it were shown that the minerals of opposing groups for other regions do not become saturated.

The reality of the limits fixed for the San Franciscan sequence of lavas by the saturation of the opposing groups of minerals is indicated by the fact that a similar result was independently obtained from the serial chemical characters of the lavas. Particularly suggestive, however, is the coincidence between the limits set to the San Franciscan sequence by saturation and those for igneous rocks in general as expressed by their silica content. The distribution curve for igneous rocks in general, which is actually the distribution curve for the silica in these rocks, is given in figure 34. It is based on 1,237 of the superior analyses in the Washington and Washington-Roth tables reduced to a water-free basis.[3] Silica is not so expressive of the composition of all igneous rocks as for the common types. However, it is more representative than any other single factor, as the common types constitute two-thirds or more of all igneous rocks. The observed irregularity in the number of analyses for successive amounts of silica is due partly to the unit of measure (1 per cent) being below significant size. A study of mineral analyses shows that a unit of 2 or 3 per cent of silica is more nearly correct, and the irregularity noted largely disappears when such a unit is used.

The interesting features of the distribution curve for silica, or for igneous rocks, are the two maxima and the abrupt decline, practically to the vanishing point, in the number of analy-

[1] Bunsen, R., Ueber die Processe der vulkanischen Gesteinsbildungen Islands: Pogg. Annslen, vol. 58, 1851, pp. 197–272.

[2] Durocher, J., Essai de pétrologie comparée: Annales des mines, 5th ser., vol. 11, 1857, pp. 217–259.

[3] This figure is taken from an unfinished statistical study of the chemical composition of igneous rocks. Certain results obtained have made it advisable to postpone the completion of the study until a new table of several thousand analyses, covering the period since 1900, has been compiled by Dr. Washington. The distribution curve for silica here given is preliminary. Its form may be somewhat modified by further study, but will not be radically changed.

ses, or rocks, having silica less and greater than the respective maxima. The greater maximum is at 50 per cent silica, and the vanishing point may be placed at 38 per cent. The lesser maximum is at 75 per cent, and the vanishing point may be placed at 79 per cent.

It will be observed that there is a very close coincidence (*a*) between the silica content of the calculated end members of the San Franciscan sequence and of the vanishing points for igneous rocks in general and (*b*) between the actual limits of the San Franciscan sequence and of the two maxima of the distribution curve. At the basic end the figures are 40.5 and 48.5 as compared with 38 and 50; at the acidic end they are 78 and 74 as compared with 79 and 75. These coincidences appear too close to be a matter of chance, and consequently it may be assumed that they represent a causal relation.

The distribution curve for silica (fig. 34), as well as the curves for the basic radicals, shows that the process by which igneous rocks are formed acts in a very definite manner to limit the range in composition. It is certainly significant that the vast majority—over 98 per cent—of all igneous rocks consist predominantly of silicate minerals and contain between 38 and 80 per cent of silica. This fact has some bearing also on the classification of igneous rocks. The restricted range is explained by considering igneous rocks as derived from solutions according to definite processes. It is not yet known what these may be for so complex a solution as an igneous magma at high temperatures and often under great pressures, but the behavior of dilute solutions, both organic and inorganic, offers suggestions.

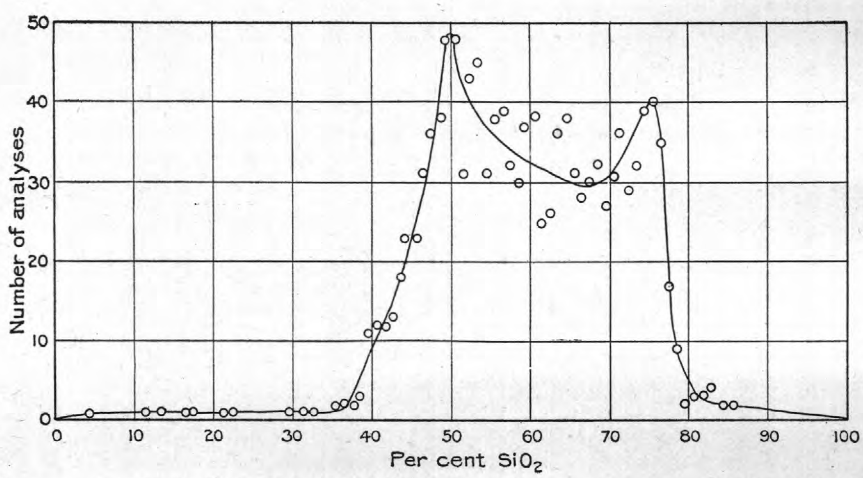


FIGURE 34.—Distribution of analyses of igneous rocks in general with respect to silica.

The limit to increasing acidity of composition in igneous rocks may be determined, as suggested by Vogt,[1] by an approximate ternary eutectic mixture of quartz and alkali feldspars. This may be the interpretation which should be placed on the saturation of the minerals of group 1—quartz, orthoclase, and albite—in their limiting position. In connection with the distribution curve for potash (for igneous rocks in general) a tentative eutectic composition for these three minerals was determined to be: Quartz, 33; orthoclase, 27; albite (including anorthite), 35; calfemic minerals, 5; total, 100. The acidic end member of the San Franciscan sequence has the following composition: Quartz, 30; orthoclase, 26; albite, 41; calfemic minerals, 3; total, 100. The only notable difference between these is the larger amount of albite in the acidic end member of the San Franciscan sequence, and in this connection the order of crystallization in the holocrystalline soda granite porphyry of San Francisco Mountain is of interest. There was first a separation of soda orthoclase and some quartz, followed by the rest of the feldspar, mostly as microperthite, and quartz, which constitute the bulk of the rock. The small amount of riebeckite apparently crystallized partly before, partly in the final stage. It is possible to suppose that the basalts, which are the actual basic limit of the San Franciscan sequence, are essentially a binary eutectic mixture of labradorite (Ab_3An_4) and augite in the proportion of about 3:2, as they form three-quarters or more of the total mineral composition of these lavas.

In view of the present incomplete knowledge in regard to eutectic proportions among rock-forming minerals, perhaps too much stress should not be laid on this phenomenon as a basis

[1] Vogt, J. H. L., Über anchi-eutecktische und anchi-monomineralische Eruptivgesteine: Norsk geologisk Tidsskrift, vol. 1, no. 2, 1905, pp. 16 et seq.

for generalizations. Petrologists have been confused for so long by the increasing evidence of variability in rock composition that anything so definite (theoretically) as an eutectic mixture may be too eagerly seized upon. The definiteness of eutectic mixtures would seem, indeed, to be an argument against their being the rule. If the common constituents of magmas at their prevailing temperatures are miscible in all proportions, it follows that eutectic mixtures, when conceived with any strictness, must be rare, because they consist of definite proportions of minerals which crystallize at a fixed temperature. A eutectic mixture is only one of a considerable number of possible mixtures in any case. The chances thus appear much against all or even the greater part of a rock being of eutectic proportions, although very probably a small part may be of such proportions. Similarly it must be supposed that the initial composition of the magmas of petrographic provinces is not in general of eutectic proportions, although as a matter of chance it may be of such proportions in a few regions.

These views are supported by the observed variability in the mineral composition of igneous rocks in general, of individual provinces, and especially of those rocks which occur at the two maxima in figure 34. The composition is decidedly variable and many rocks consist simply of different amounts of the same minerals. It may be concluded that the two maxima are not determined by eutectic proportions in all the rocks so located; on the other hand, some proportion of these rocks are no doubt eutectic mixtures.

The observed variability in composition among igneous rocks, and especially the successive gradations of such a series of rocks as that of the San Franciscan volcanic field, favor the suggestion that differences in the composition of an originally homogeneous magma arise from changes in temperature and pressure in connection with actual crystallization. The subject is too large to be discussed here. It has been assumed that the composition of the great mass of rocks is acquired in the magmatic reservoir and that a rock has the same composition as the magma of which it is a crystallized part, except as regards its gaseous content. If eutectic proportions in igneous rocks are considered the rule, rather than the exception, it is necessary under these conditions to suppose that they exist in the magma. It follows, then, that a magma would be erupted only when it had reached eutectic proportions. This idea, of course, can not be seriously entertained. A magma is erupted not because it has a particular composition, but because physical conditions in the earth's crust are favorable to its expulsion.

In conclusion it may be said, however, as is shown by the distribution curve for silica (fig. 34), that whatever is the actual process which governs the formation of igneous rocks, it operates in a most definite manner to limit their range in composition.

It will be observed in the distribution curve for silica (fig. 34), which approximately represents the distribution of igneous rocks with respect to their composition, that the maximum at 50 per cent is greater than that at 75 per cent and that the decrease to a minimum from the former covers a wider range of silica. This is due simply to the larger number of minerals which may form the more basic rocks. That is, a greater number of combinations is possible at the basic maximum than at the acidic maximum. In general the curve expresses the fact that those rocks occurring most frequently consist of the largest number of minerals, whereas those of least frequency consist of the smallest number. For high silica this is self-evident; a rock containing 100 per cent of quartz would be monomineralic. It is also true at the opposite extremity of the curve, where the dunites, titaniferous iron ores, and corundum rocks are essentially monomineralic or duomineralic.

SPECIFIC GRAVITIES.

The specific gravities of the lavas of the San Franciscan volcanic field, calculated on the basis of holocrystallinity, no less than the serial chemical and mineral characters, furnish very strong evidence in support of the conclusion that all the rocks were derived from a homogeneous parent magma according to definite laws. The measured specific gravities also exhibit an interesting relationship but are of less value for this purpose on account of variations caused by differences in the crystallinity of the lavas, as well as errors due to the method of determining them.

These points are very clearly brought out in figure 35, where the specific gravities are plotted as a function of the composition of the rocks, which, as in the case of the serial mineral characters, is represented by silica.

The specific gravities of the lavas as holocrystalline rocks have been calculated from their mineral compositions, as given in the table on page 189, by using the following specific gravities for the component minerals:

Quartz, 2.65.	Anorthite, 2.76.	Riebeckite, 3.3.	Augite, 3.3.	Apatite, 3.2.
Orthoclase, 2.56.	Corundum, 4.00.	Hornblende, 3.3.	Olivine, 3.5.	Ilmenite, 4.7.
Albite, 2.60.	Biotite, 2.9.	Hypersthene, 3.5.	Garnet, 3.5.	Magnetite, 5.2.

All the plagioclase has been resolved into albite and anorthite; also the ore into magnetite and ilmenite. In the basic lavas all the pyroxene has been calculated as augite, as that is its mode of occurrence. The specific gravities of the hornblende, pyroxene, and olivine have been placed at a rather high figure on account of the iron-rich character, in general, of these minerals.

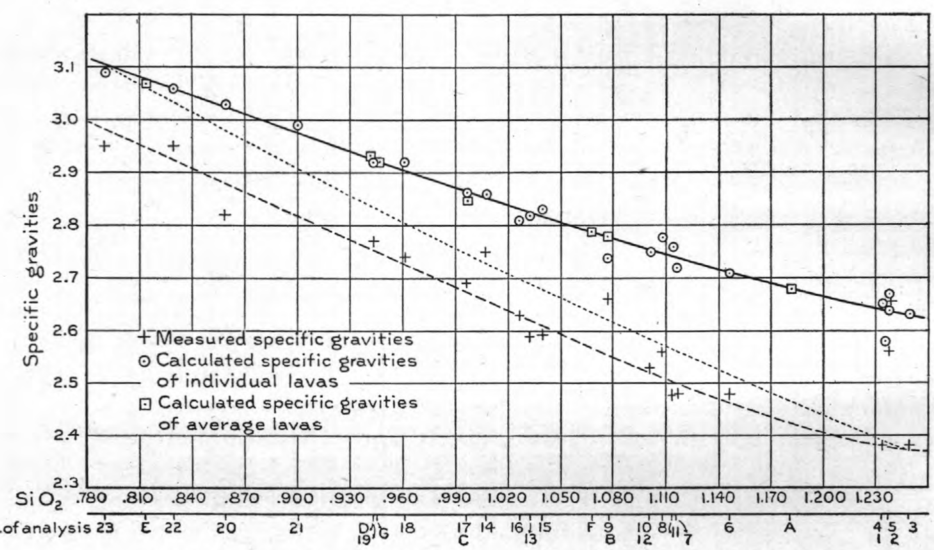


FIGURE 35.—Specific gravities of lavas of the San Franciscan volcanic field.

The continuity of the relation between the calculated specific gravities, shown in figure 35, is indeed most striking; there is not a discordant member in the entire series. The specific gravities of the average lavas of the region fit the curve with a high degree of precision, which is significant of the correctness of the calculated values as a whole, as they were plotted after the curve had been fitted to the specific gravities of the individual lavas. It will be seen that the calculated amounts are practically a linear function of silica throughout the series, and that this relation is strictly true for that part extending from the basalts through the acidic dacites (SiO_2, 0.780 to 1.140).

The measured specific gravities also exhibit a more or less continuous relation, although there are certain errors to be noted in their determination. The relation depends on the crystallinity of the lavas, which is a function of their composition, as is shown in a succeeding section dealing with this subject (pp. 207–209). The basalts are holocrystalline, whereas the rhyolites are holohyaline, and the fact that the lavas situated between the two extremes of the series show on the whole a marked continuity of relationship evidently indicates a decidedly uniform decrease in their crystallinity with increasing acidity in chemical composition. The divergence of the measured from the calculated specific gravities toward the acidic end of the series expresses the fact that the density of the lavas decreases as the percentage of glass increases more rapidly than it would in a series whose members were holocrystalline throughout.

The measured specific gravities of the two holocrystalline basalts (Nos. 22 and 23) should coincide with their calculated values, but actually they are about 4 per cent too low. This brings out the point that the method of determining specific gravities on a single rock fragment of some 20 grams weight, even though it is holocrystalline, can not be depended on to give correct results. The errors in the measured values of the four holocrystalline members of the series are as follows:

Specific gravities measured and calculated, with percentage of error, of granite porphyry and basalt of San Franciscan volcanic field.

No.	Rock.	Specific gravity.		Error (per cent of calculated specific gravity).
		Measured.	Calculated.	
2	Granite porphyry	2.56	2.64	3.0
5	Granite porphyry	2.66	2.67	.4
22	Basalt	2.95	3.06	3.6
23	Basalt	2.95	3.09	4.5

The error in the measured value of No. 5 is very slight. In the other three rocks it is much too large to be accounted for by the presence of small amounts of glass and consequently it must be due to the incomplete expulsion of air in boiling and possibly to occluded gases.

The measured specific gravities of the two rhyolite glasses (Nos. 3 and 4), on the other hand, are essentially correct, as may be seen from the following figures:

Specific gravities, measured and calculated, with per cent of error, of rhyolites of San Franciscan volcanic field.

No.	Specific gravity.		Error.
	Measured.	Calculated.	*Per cent.*
3	2.37	2.36	0.4
4	2.38	2.38	0

The calculated specific gravities were obtained from the modes by using the following specific gravities for the component minerals in a glassy condition: Quartz, 2.23; orthoclase, 2.40; albite, 2.38; anorthite, 2.70; hornblende, 2.85.

The correct measured specific gravities, therefore, should lie along a line, whose position is approximately indicated in figure 35, joining the measured values of the rhyolites and the calculated values of the basalts. The actual measured specific gravities thus diverge from the probable measured values toward the basic end of the series, from which it would appear that the error was due to the increasing crystallinity of the rocks.

On the assumption that the position of the line joining the measured values of the holohyaline rhyolites and calculated values of the holocrystalline basalts is approximately correct, the following corrections should be added to the measured specific gravities:

Rhyolites (holohyaline), 0.
Acidic dacites (hypohyaline), 2.4 per cent of the measured specific gravity.
Soda dacites (hypocrystalline), 2.7 per cent of the measured specific gravity.
Latites (hypocrystalline), 3 per cent of the measured specific gravity.
Andesites (hypocrystalline), 3.1 per cent of the measured specific gravity.
Basalts (holocrystalline), 4 per cent of the measured specific gravity.

The differences between the corrected measured specific gravities of these lavas and the calculated values for the same in a holocrystalline condition, expressed as a percentage of the measured values, are as follows:

Rhyolite, 10 per cent.
Acidic dacite, 7.2 per cent.
Soda dacite, 6 per cent.
Latite, 4.2 per cent.
Andesite, 3 per cent.
Basalt, 0.

The difference for the rhyolite is the maximum, as the lava is holohyaline; that for the basalt is the minimum, as the rock is holocrystalline. For the intermediate varieties the degree of crystallinity may be calculated approximately from the modes of the lavas. Thus to secure the indicated differences the following amounts of the component minerals must be in a glassy condition:

Acidic dacite: All the quartz and orthoclase and 85 per cent of the albite; equals 65 per cent of the rock.
Soda dacite: All the quartz, orthoclase, and albite; equals 65 per cent of the rock.
Latite: All the quartz and orthoclase and 75 per cent of the albite; equals 47 per cent of the rock.
Andesite: All the quartz and orthoclase and 50 per cent of the albite; equals 29 per cent of the rock.

These results are, of course, only approximate and it would be too much labor to check them on account of the difficulty of estimating the relative amounts of glass and microscopic crystals in the groundmass of the lavas. The test may be most easily applied to the andesites. The 28 per cent of hyaline groundmass in the andesite of San Francisco Mountain and the 32 per cent in that of Kendrick Peak agree closely with the average calculated value of 29 per cent. This should be accepted as indicating the general correctness of the calculated results.

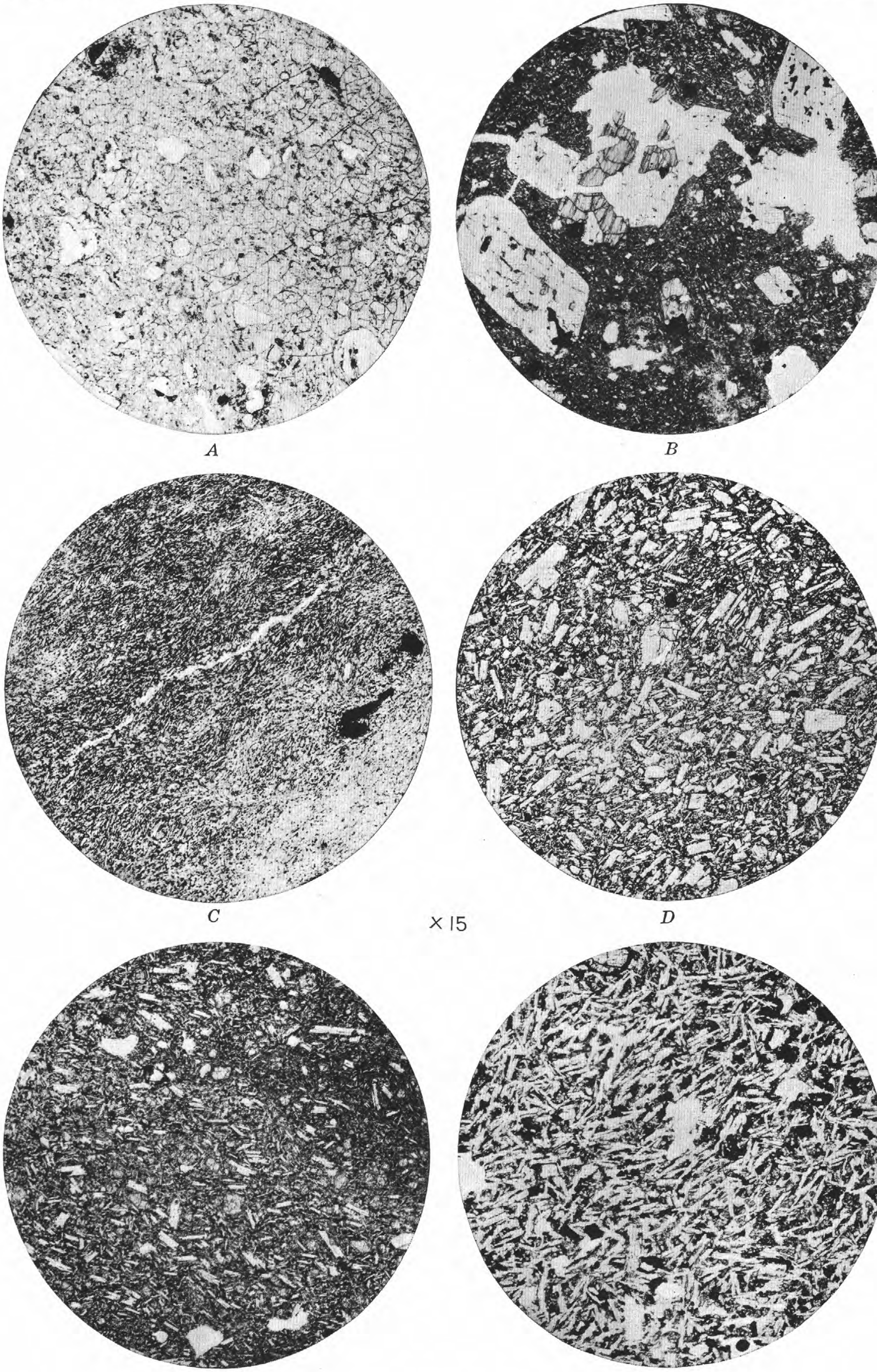
TEXTURE.

The different textures which are distinguished are the rhyolitic, dacitic, latitic, andesitic, and basaltic. It is, perhaps, not necessary to give any detailed description of these textures beyond noting some of their chief features. In general, they are the same as the textures found in rocks of similar composition to those of the San Franciscan region. The wide range in the crystallinity of the lavas, except the basalts, gives rise to many minor varieties. An idea of these textures, as typically developed, may be obtained from the selected specimens which are reproduced in Plate XIV. When the different rock types have become sufficiently familiar, it is possible to recognize them with nearly the same degree of precision by their megascopic textural characters as by their appearance in thin section. The textures of the different lavas are thus fairly definite and, what is more interesting, they persist through a considerable range in chemical composition.

The rhyolitic texture is easily distinguished from all others as predominantly holohyaline or spherulitic. An interesting point is the persistence of this texture in the biotite dacites of Kendrick and O'Leary peaks, which are considerably more basic in composition than the true rhyolites. They have not only the typical textures but also the normal mineral composition of the rhyolites. These two associations are considered sufficient ground for grouping them with the rhyolites rather than the dacites, as has been done in calculating the average composition of the main rock types of the region and in the discussion of the differentiation of the lavas in space. Classification by chemical or complete mineral composition thus separates rocks that would be grouped together according to origin under similar physical conditions, as indicated by like textures.

The dacites are the only lavas that are characteristically porphyritic; they have some 25 per cent of plagioclase and calfemic minerals in a hyaline to microcrystalline groundmass. The dacites of Kendrick and O'Leary peaks are more basic than the other members of this group. However, this change in composition produces no evident change in the texture, which remains typically dacitic. A striking feature of the dacites, structural rather than textural, is the tendency they exhibit to form dome-shaped cones and massive flows. This is most highly developed in the lava of Elden Mountain and led Lieut. Whipple to call this lava a "granite." This mode of occurrence is interpreted as due to a high degree of viscosity.

The typical latitic texture may be considered as trachytic and nonporphyritic. The degree of crystallinity is about the same as in the groundmass of the dacites and when phenocrysts are present in considerable amount (as in some specimens) it is somewhat difficult to distinguish the two lavas in thin section. A very characteristic feature of the latites is a thin, platy flow structure. It is best developed in the lavas of Mormon Mountain and Crater Hill (Observatory Mesa) and to a less extent in those of San Francisco Mountain.



PHOTOMICROGRAPHS OF TYPICAL LAVA TEXTURES.

A, Soda rhyolite; *B*, soda dacite; *C*, latite; *D*, andesite; *E*, basalt of first period of eruption; *F*, basalt of third period of eruption.

The andesites have the texture described as hyalopilitic, which is characteristic of this type of lava. Contrary to what occurs in the rhyolites and dacites, increasing basicity in composition causes a change in texture. The typical andesites of San Francisco Mountain and Kendrick Peak are easily distinguished from the basalts. The more basic andesite of Bill Williams Mountain, on the other hand, so far approaches a basalt, especially in megascopic appearance, that it is difficult to distinguish it from some of the more dense recent basalts.

The texture of the basalt, of both the first and the third periods of eruption, is typically doleritic. The basalts are the only holocrystalline lavas in the region and are nonporphyritic, except for the small amount of olivine.

CRYSTALLINITY.

It has already been observed in the discussion of the specific gravities that a close relation exists between the crystallinity and the chemical composition of the lavas of the San Franciscan volcanic field. This point may be taken up in more detail, for which purpose the micrometric analyses of the rocks are collected in the following table:

Micrometric analyses of lavas of the San Franciscan volcanic field.

No.	Ground-mass.	Feldspars.	Calfemic minerals.	Group.
	Per cent.	*Per cent.*	*Per cent.*	
1	87	11	1	Rhyolite.
2	(Holocrystalline intrusive.)			
3	100			
4	100			
5	(Holocrystalline intrusive.)			
6	77.3	18.3	4.4	Acidic dacite.
7	90.0	10.0		
8	69.8	22.1	8.1	Dacite.
9	76.6	16.7	8.7	
10	72.8	18.5	8.7	
11	71.3	18.6	10.0	
12	77.2	11.6	11.2	
13	71.5	18.5	10.0	
14	66.5	22.0	11.5	
15	78.5	10.7	10.8	
16	90.0	5.0	5.0	Latite.
17	81.4	14.8	3.8	
18	27.7	52.9	19.4	Andesite.
19	32.2	53.2	14.6	
20	(Not measured.)			
21	37.0	12.5	50.5	
22	1.9	50.7	47.3	Basalt.
23	0	50.8	49.1	

The crystallinity, as above given, is that of each single type-specimen. It shows, therefore, the average crystallinity of each rock mass. The type-specimens do not, however, correctly represent the average crystallinity of some of the lavas. This is true of the rhyolite glasses, Nos. 3 and 4, for this lava commonly has a hypomicrocrystalline texture; the types were selected for analysis because of their perfect freshness. However, if the minor differences in crystallinity, such as are expressed by a change from hyalinity to microcrystallinity, are disregarded and comparisons made between the groundmass and those minerals which have crystallized in measurable sizes (that is, of greater diameter than 0.01 millimeter), several definite results appear.

The analyses, with certain significant exceptions, show a progressive decrease in the amount of groundmass and increase in feldspars and calfemic minerals as the lavas become more basic in composition. The changes, however, are not regular and the several rock groups may be clearly distinguished by their degree of crystallinity.

Thus Nos. 1, 3, and 4 are rhyolites of which two members consist of 100 per cent groundmass—they are actually holohyaline—and the third contains a large amount and is also characterized by very low calfemic minerals. Nos. 6 and 7 are acidic dacites, which are texturally related to the rhyolites. No. 6 has the same degree of crystallinity as the dacites, from which, however, it is distinguished by texture and low calfemic minerals, whereas No. 7 is typically rhyolitic. Nos. 8 to 15 cover the dacite group. These have a smaller proportion of groundmass and larger amounts of feldspars and calfemic minerals than the rhyolites. The latites, Nos. 16 and 17, are clearly an exception to the general rule that the groundmass decreases and measurable components increase as the lavas become more basic. The andesites, Nos. 18 to 21, however, have a much smaller proportion of groundmass and larger amounts of measurable crystals, except No. 20, than any of the more acidic lavas. No. 21, the hornblende andesite-basalt of Bill Williams Mountain, which occurs as a secretion in the dacites, is an abnormal member of the series with respect to the relative amounts of feldspar and calfemic minerals, but not as to their total amount. In the basalts, Nos. 22 and 23, the groundmass practically disappears and the lavas become holocrystalline, being composed of nearly equal amounts of plagioclase and calfemic minerals.

The differences in the crystallinity of these groups of lavas may be more clearly brought out if the micrometric analyses of each are averaged as appears in the following table:

Average micrometric analyses of lavas of San Franciscan volcanic field.

	Groundmass.	Feldspars.	Calfemic minerals.	Feldspars + calfemic minerals.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*
Rhyolite	96	4	0.5	4.5
Acidic dacite	84	14	2	16
Dacite	73	17	10	27
Latite	86	10	4	14
Andesite	30	53	17	70
Basalt	1	51	48	99

Presented in this manner, the decrease in the groundmass and increase in measurable crystals, or, in general, the increasing crystallinity of the lavas with increasing basicity of composition, is evident, except for the latites. It is interesting to observe that the relation is

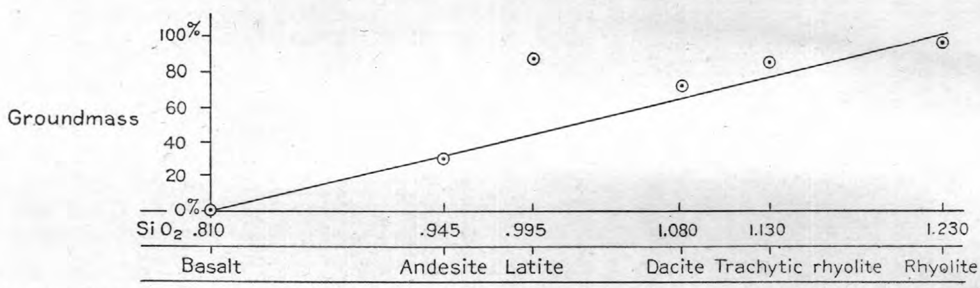


FIGURE 36.—Relation between amount of groundmass and chemical composition of the lavas of the San Franciscan volcanic field.

practically a linear one, as is shown in figure 36. The values for the groundmass, in all groups except the latites, lie close to a straight line joining 0 per cent of the groundmass in the basalts and 100 per cent in the rhyolites. This would seem to emphasize the conclusion, based on the serial mineral characters, that the physical conditions under which the lavas were erupted, with a single exception, were very uniform throughout the volcanic activity of the region, notwithstanding the wide range in the composition of the erupted lavas.

There is apparently nothing about the composition of the latites which should cause them to depart from the linear relation of crystallinity to composition shown by the other lavas. Consequently it must be inferred that their exceptional crystallinity resulted from some peculiarity in the physical conditions under which they were erupted. An unusually high viscosity does not appear to be indicated by the topographic form of the flows; it is probable, indeed, that some of the dacites were more viscous than the latites. Possibly a low temperature, due to the loss of occluded gases, and a consequent rapid cooling, may be the explanation. The first stage of activity in San Francisco Mountain, during which latite was erupted, was predominantly explosive; on the other hand, explosive phases did not occur at Mormon Mountain and Crater Hill, to judge from the absence of fragmental material.

The augite andesite-basalt of Bill Williams Mountain, No. 20, also has an exceptional crystallinity. It is very fine-grained, too fine to measure, although the andesites and basalts are the most coarsely crystalline lavas of the region. The type specimen was taken from a lava fragment which occurs in a breccia, so that rapid cooling presumably explains the fine grain of this rock.

GRANULARITY.

An idea of the granularity of the rocks of the San Franciscan volcanic field may be obtained from the average diameters of the component minerals as measured by the Rosiwal method. The figures given are for the single type specimens. They show, therefore, the average granularity of each rock mass only so far as the selected specimen is typical of it. In the following table, which presents these measurements, the rocks are arranged in the same order as in the other tables in this chapter.

Average diameter, in millimeters, of minerals of type rocks of San Franciscan volcanic field.

No.	Feldspars.	Calfemic silicates.	Magnetite.	Remarks.
1				Not measured.
2				Holocrystalline. Average grain (estimated), 0.025 millimeter
3				Holohyaline.
4				Holohyaline.
5				Holocrystalline. Average grain, 0.025 millimeter.
6	0.45	0.18	0.04	
7				Not measured.
8	.09	.26	.02	
9	.38	.26	.08	
10	.75			Calfemic minerals, 0.13 millimeter.
11	.07	.06	.02	
12	.10	.06	.02	
13	.14	.07	.03	
14	.22	.14	.03	
15	.22	.07	.03	
16				Not measured.
17	.40	.22	.08	
18	.06	.02	.02	Olivine phenocrysts, 0.10 millimeter. Average grain, excluding groundmass, 0.04 millimeter.
19	.06	.02	.01	Feldspar phenocrysts, 0.75 millimeter. Olivine, 0.06 millimeter. Average grain, excluding groundmass, 0.04 millimeter.
20				Not measured.
21	.15	.50	.06	Porphyritic.
22	.08	.04	.04	Olivine phenocrysts, 0.17 millimeter. Average grain, 0.07 millimeter.
23	.025	.015	.012	Olivine phenocrysts, 0.10 millimeter. Average grain, 0.027 millimeter.

NOTE.—Groundmass, when present, has a grain very much less than 0.01 millimeter in diameter.

The rocks given in the above table roughly fall into two groups, the porphyritic and nonporphyritic, with, however, many exceptions. The porphyritic group includes the dacites and in part the latites, Nos. 6 to 17; also the hornblende andesite-basalt, No. 21. The nonporphyritic group consists of rhyolites, andesites, basalts, and in part latites, Nos. 1 to 5, 16 to 20, 22, and 23.

All the rocks are distinctly fine grained, for in none does the average diameter of any mineral exceed 1 millimeter. This is especially true of the lavas of intermediate and acidic composition, in which the groundmass, forming over three-fourths of the rock, ranges from hyalinity to microcrystallinity and consequently is, at a maximum, exceedingly fine grained.

Of the rhyolites proper two, Nos. 3 and 4, are holohyaline and the third, No. 1, is porphyritic. In the dacites the feldspar phenocrysts are exceedingly variable in size, the higher averages generally resulting from the presence of exceptionally large crystals. The size of the calfemic silicates is greatest in the two dacites of San Francisco Mountain, Nos. 8 and 9; in the other dacites it tends toward constancy. As the percentage of the calfemic silicates is approximately the same in all the dacites, the lavas of San Francisco Mountain contain a smaller number of phenocrysts of larger size. Magnetite in the dacites shows a general uniformity in size, the average being between 0.02 and 0.03 millimeter. The latite of Mormon Mountain, No. 16, is so fine grained and free from phenocrysts that it was not measured. In the latite of San Francisco Mountain, No. 17, the feldspar, calfemic silicates, and magnetite approach the larger sizes found in the dacites. These figures should not be given too much weight, as the type specimen does not adequately represent the entire mass. It is in part nonporphyritic.

The sizes of the feldspar and augite in the andesites of San Francisco Mountain and Kendrick Peak, Nos. 18 and 19, are the same, but magnetite and olivine are smaller in the latter.

The average grain of both rocks is 0.04 millimeter, with the groundmass omitted and also the large feldspar phenocrysts of the lava of Kendrick Peak. The grain of the andesite-basalt of Bill Williams Mountain, No. 20, is too fine to be measured.

The basalt of the first period of eruption, No. 22, is the most coarsely crystalized rock of the region, although the average grain is but 0.07 millimeter. The basalt of the third period, No. 23, is much finer grained, the average being 0.027 millimeter. This is a characteristic difference between these two lavas. The finer grain of the recent basalt is probably due to greater viscosity, as the composition of the two lavas is practically the same. It will be recalled that the basalt of the third period occurs in rather thick flows of small extent as compared with the widespread thin flows of the basalt of the first period.

Holocrystalline intrusives having the same composition as the rhyolites occur at San Francisco Mountain, No. 5, and Marble Hill, No. 2. The measured average grain of the first is 0.025 millimeter, and that of the porphyry of Marble Hill is estimated to be the same. These acidic intrusives have, therefore, the same grain as the recent basalt and are finer grained than the andesites and old basalt.

A general idea of the granularity of the different groups of lavas may be obtained by averaging the members that compose them. The results are as follows:

Average granularity of lavas of San Franciscan volcanic field.

[Size of grains in millimeters.]

	Feldspars.	Calfemic silicates.	Magnetite.	Remarks.
1. Rhyolite	Holohyaline, nonporphyritic. Average grain of holocrystalline intrusive representatives, 0.025 millimeter.			
2. Acidic dacite	0.45	0.18	0.04	Has rhyolitic texture.
2. Dacite	.25	.12	.03	
2. Latite	.40	.22	.08	
3. Andesite	.06	.02	.015	Olivine phenocrysts, 0.08 millimeter. Average grain, 0.04 millimeter.
3. Basalt	.05	.03	.025	Olivine phenocrysts, 0.13 millimeter. Average grain, 0.05 millimeter.

NOTE.—1 and 3, essentially nonporphyritic; 2, porphyritic. Groundmass, where present, has a grain very much less than 0.01 millimeter.

The dacite group is most representative, because it is based on the largest number of specimens; the acidic dacite and latite groups are the least representative, for each is based on a single specimen. The average grain of the basalt is larger than that of the andesite because of the greater number and size of the olivine phenocrysts.

The degree of granularity indicates that the minerals, except the small proportion of phenocrysts, crystallized after the eruption of the lavas and while they were rapidly cooling. The temperature of the magma, therefore, was sufficiently above the freezing point to keep it in a thoroughly uncrystallized condition in the vents of the volcanoes.

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