# Petrology of Parícutin Volcano Mexico

*By* RAY E. WILCOX

## GEOLOGIC INVESTIGATIONS IN THE PARÍCUTIN AREA, MEXICO

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# PETROLOGY OF THE PARICUTIN VOLCANO

By Ray E. Wilcox

## ABSTRACT

Parícutin volcano, Mexico, remained in active eruption from its birth, February 20, 1943, until March 4, 1952. During this period of 9 years, the eruption of lava and vapors was remarkably continuous; eruption of pyroclastic material was somewhat spasmodic, with some periods of a month or more during which practically no pyroclastic material was thrown out. With rare exceptions the sites of lava eruption were at either the northeastern or southwestern base of the main cone, and lava emission alternated between these sites from time to time. The total area of old land covered by lava during the 9-year eruption is 24.8 square kilometers, and the total rock material erupted is estimated to have occupied about 1.4 cubic kilometers in the magma chamber.

A progressive change in composition is noted in successive ejecta of Parícutin volcano. Ejecta of 1943 are of olivine-bearing basaltic andesite containing 55 percent silica. Succeeding ejecta are progressively more salic, until in 1952 the ejecta are of orthopyroxene andesite containing over 60 percent silica. With the exception of a sharp decrease in magnesia and increase in silica in 1947, this change in composition of successive ejecta was fairly regular. The ejecta of 1943 and of the first part of 1944 are characterized by small numbers of olivine and plagioclase megaphenocrysts in groundmasses of plagioclase, olivine, clinopyroxene, orthopyroxene, opaque oxide, and glass. Plagioclase megaphenocrysts are virtually absent in ejecta after 1944. In ejecta of 1945–1952, the olivine megaphenocrysts carry coronas of fine-grained hypersthene; and in ejecta of late 1947, olivine megaphenocrysts are scarce and remain so in successive ejecta through the close of eruption in 1952. Clinopyroxene megaphenocrysts occur only rarely and clinopyroxene microphenocrysts only in the ejecta of 1943–44 and in some ejecta of 1946. Orthopyroxene, which becomes more abundant and larger in size in the groundmasses of successive pre-1947 ejecta, occurs also as megaphenocrysts in ejecta of 1947 and later. In the individual mineral series there appears to be only a slight tendency towards more salic compositions of the minerals themselves in the later erupted materials, although the bulk rock compositions become definitely more salic. Compositions of plagioclase megaphenocrysts average near $An_{70}$, those of olivine near $Fo_{80}$, and those of orthopyroxene near $En_{75}$, as inferred from optical properties. Groundmass orthopyroxene is consistently poorer in magnesia than the megaphenocrysts of the same specimen. The glassy mesostases of later erupted specimens have lower refractive indices than those of early erupted specimens, indicating more salic compositions.

Xenoliths of granite, quartz monzonite, dacite tuff and other rock types are found in the ejecta of Parícutin volcano and are presumed to represent some, at least, of the types of country rock at depth. All stages of melting, inflation, and mutual solution of the mineral components of the xenoliths are seen, but there seem to be only a few easily recognized examples of intimate strewing of xenolithic

material through the normal ejecta, and the visible transition zones between lava and xenolith do not usually exceed a few millimeters in width. Xenocrysts of quartz and feldspar occur sporadically in a few lava specimens that appear to be otherwise normal.

On the basis of graphical tests using the chemical and petrographic data, it is concluded that fractional crystallization alone could not have caused the observed differences between successive ejecta. A combination of fractional crystallization (involving olivine and plagioclase) and assimilation of salic country rock is shown, by use of the silica-variation diagram, to satisfy closely the chemical relationships between the lavas; and rough calculations indicate that the heat required for this process appears to be available by convection without superheat if a reasonable configuration of the magma cupola is assumed.

## INTRODUCTION

Parícutin volcano is located in the State of Michoacán, Mexico, about 320 kilometers due west of Mexico City, at lat. 19°29′33″ N., long. 102°14′59″ W. (fig. 95). The eruption began suddenly February 20, 1943, and continued without major interruption for 9 years. The eruption of lava ceased suddenly on February 25, 1952; and after a few explosive surges, the eruption of pyroclastics ceased completely on March 4, 1952. The purpose of this paper will be to examine the remarkable continuity of eruptive activity and an equally remarkable progressive change in composition of successively erupted material from basaltic andesite of 55 percent silica in 1943 to andesite of slightly over 60 percent silica at the end of the eruption in 1952.

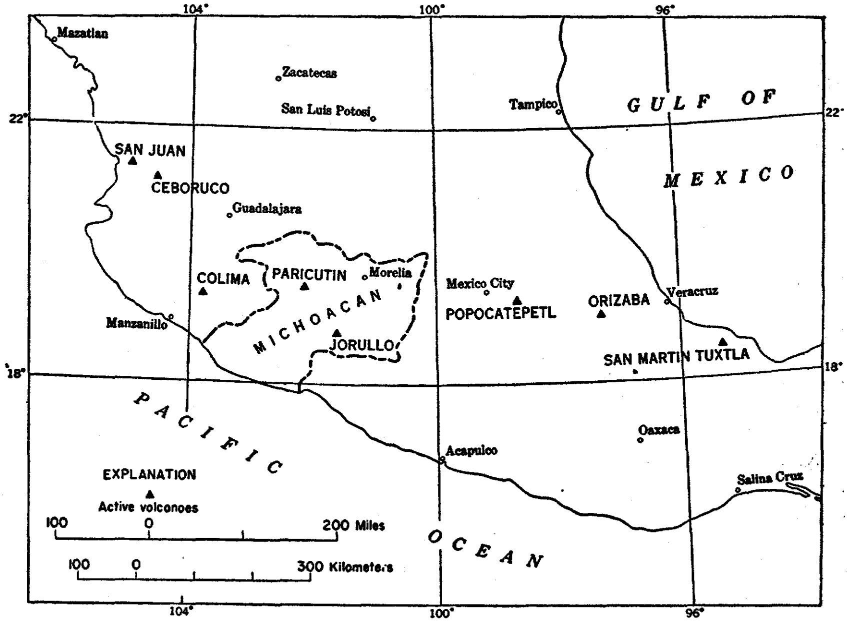

FIGURE 95.—Map of central Mexico showing location of Parícutin and other volcanoes active since 1519.

Many scientific pilgrimages have been made to Parícutin volcano, which, with its easy accessibility, has offered opportunity to study the life cycle of a volcano from its very beginning, as well as to study the effects of a prolonged eruption on the ecology and economy of a rural area. Bibliographies of published results of some of these studies have been included in earlier chapters of this bulletin (Segerstrom, 1950, p. 4–6, and Williams, 1950, p. 272–274), and it is necessary here only to mention a few other references that have appeared more recently. Reports of the eruptive activity for 6-month intervals have been made by Fries and Gutiérrez (1950a, b; 1951a, b, 1952a, b; and 1954. A detailed description of the activity of the volcano during the first 2 years is being furnished by Foshag and González.

The present study began with a period of essentially continuous observation of the activity of Parícutin volcano by the writer from September 1946 through May 1948, and thereafter observations were confined to short monthly visits until December 1948. Specimens of the erupted material collected then, together with specimens collected by other investigators before and after the period of the writer's field work, form the basis of the petrographic and chemical portions of this study.

The field investigation during 1946–48 was carried out with the support of the U. S. State Department's program of Scientific and Cultural Cooperation with the American Republics. For aid and advice during the investigation, the writer is especially indebted to Carl Fries, Jr., Richard E. Fuller, Howel Williams, Eduardo Schmitter, J. A. Hernández Velasco, S. Shoup Oropeza, Celedonio Gutiérrez, Antonio Saldaña, and Jesus Saldaña. The house at Cuzeño Station, 5 kilometers north of the active cone, was made available as an observatory by the Geological Society of America, which also supported the work in many ways through the U. S. Committee for the Study of Parícutin volcano. Calculations of tidal force at Parícutin from 1946 through 1948 were kindly furnished by the U. S. Coast and Geodetic Survey.

For specimens and thin sections of Parícutin lavas, bombs, and xenoliths to augment his own collection, the writer thanks Eduardo Schmitter and J. A. Hernández Velasco, of the Instituto de Geología de México; S. Shoup Oropeza, of Recursos Hidralicos de México; Konrad B. Krauskopf, of Stanford University; F. H. Pough, of the American Museum of Natural History; and Carl Fries, Jr. and Donald E. White, of the U. S. Geological Survey. The writer is grateful to Konrad B. Krauskopf for permission to use six unpublished chemical analyses. Field notes of early activity were kindly made available by Celedonio Gutiérrez, Howel Williams, Konrad B. Krauskopf, Donald E. White, and the late Ezequiel Ordóñez. The manuscript of the

present report was read and criticized by Richard E. Fuller and several of the writer's colleagues in the Geological Survey, to whom the writer owes many thanks, while retaining responsibility for any misstatements or faulty reasoning.

## HISTORY OF THE ERUPTION[1]

The eruption of Parícutin volcano began February 20, 1943, after several weeks of local earthquakes of increasing frequency and intensity. After the onset of the eruption, no intense local earthquakes occurred. No previous vent appeared to have been situated at the particular point of outbreak (González and Foshag, 1947) although there are many extinct cones within a radius of a few kilometers (Williams, 1950, pl. 8). The site of outbreak is 6½ kilometers SSW. of the village of Angahuan, near the northeast base of Cerros de Tancítaro, at an elevation estimated to have been 2,398 meters above sea level, (Fries and Gutiérrez, 1951b, table 4).

The growth of the resulting cinder cone was rapid. On the morning of February 21, it was estimated to be 10 meters high and by noon to be some 30 to 50 meters high. On the night of February 22, Ordóñez (1947, p. 26) estimated the height to be 60 meters and on February 26, some 150 meters. On March 2 it was measured instrumentally as 165 meters in height and 560 meters across the base in an east-west direction. Huge masses of plastic lava were thrown out bodily onto the flanks, in addition to the great quantities of moderate sized bombs and lapilli, to contribute significantly to the rapid growth of the cone.

The first lava had already started to flow, by the night of February 22 (Ordóñez, 1947, p.26 and 29), and to move eastward from the now sizable cone. Although the record of lava emission until October of the first year is not complete, it appears that the emission was all from the north and northeast sides of the cone and that, although especially strong surges or fountaining occurred from time to time, there were few periods during which lava was not flowing. Eruption of ash and bombs from the main vent was generally very copious during the first 8 months.

On October 18, 1943, a series of new lava vents broke out along a line about N. 60° E. from the NE. base of the cone and within a few days lava emission became concentrated at one vent, named Sapichu,[2] about 800 meters northeast of the main vent of the cinder cone. Appreciable amounts of pyroclastics were erupted from this vent, while steam, but no significant amounts of pyroclastics, were erupted

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[1] A detailed account of the first 2 years of eruption of Parícutin is being prepared by W. H. Foshag and J. González and a compilation of subsequent activity is being prepared by the writer for publication by the Geological Survey. For purposes of the present paper, only a brief resumé will be given.

[2] In the spellings of Tarascan geographic names the writer follows those suggested by Fries (in Segerstrom 1950, p. 153-161), which depart to a minor extent from the spellings given in previous papers.

from the main cone during the several months life of the Sapichu vent. The flow of lava from Sapichu kept the northeastern side of its own cinder cone open, so that the resulting pile of pyroclastics became crescentic in shape.

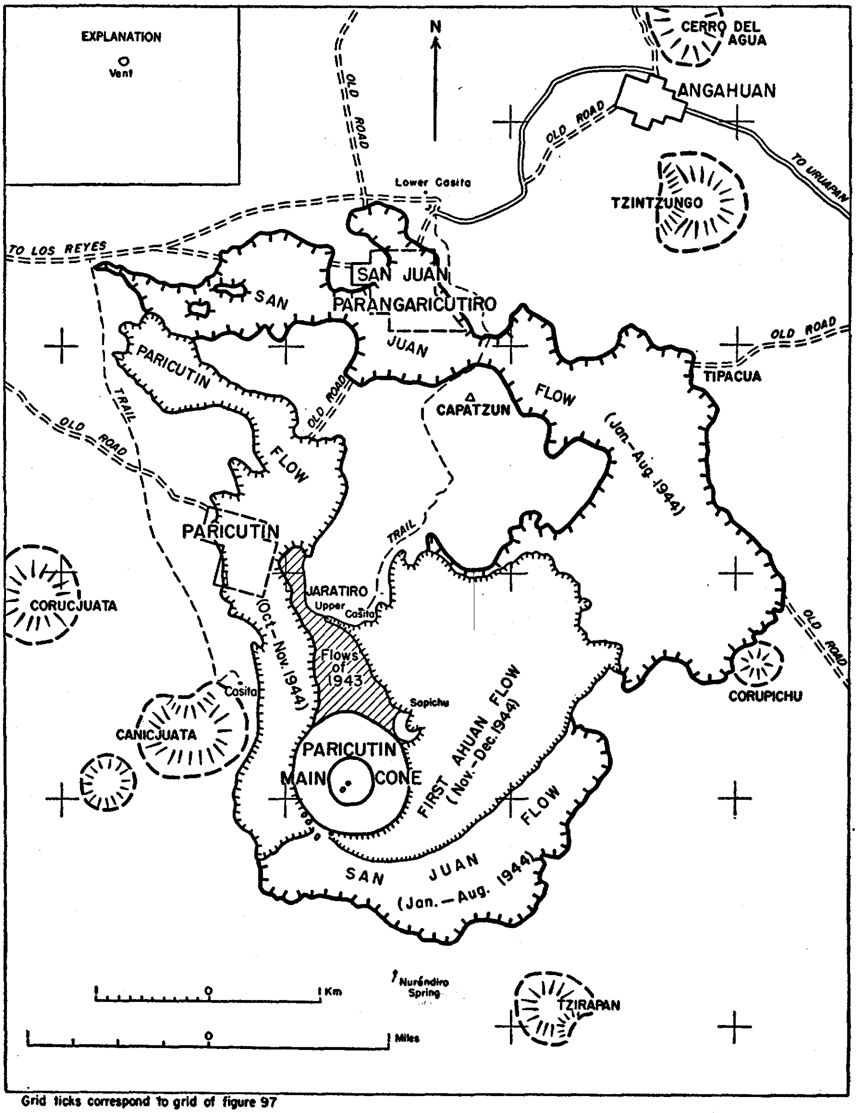
On January 8, 1944, immediately after the cessation of activity of Sapichu, multiple lava vents were opened at and near the southwest base of the main cone, and strong eruption of pyroclastics was resumed from the vent of the main cone. The area of lava vents became known as the Mesa de los Hornitos because of the profusion of hornitos. With the possible exception of part of April, the effusion of lava was copious and continuous, giving rise to the great San Juan flow, which overwhelmed the town of San Juan Parangaricutiro in July and continued for a total distance of 9 kilometers before finally ceasing in August or September 1944 (fig. 96).

In September 1944 a new vent, called Taqui, and in early November another, called Ahuán, opened on the southwestern base of the cone. Effusion of lava from the Taqui vent was not well recorded and may or may not have been continuous. During November and December the Ahuán vent furnished copious effusions of lava, which spread eastward and northeastward from the cone. The general outline of the Parícutin lava field had been delineated by the end of 1944 (fig. 96), and subsequent flows to the end of the eruption in 1952 were to pile up on previous flows for the most part and to extend the ultimate border only slightly (fig. 97).

During 1945 the eruption of lava continued, apparently alternating between the Ahuán and Mesa de los Hornitos vents near the southwest foot of the cone (Krauskopf and Williams, 1946). Observations during April to October were sporadic and not resumed systematically until October from which time until the end of the year lava emission from the southwestern vent complex was continuous (Krauskopf, 1948a, p. 721–726).

The lava activity continued from the Mesa de los Hornitos vents during the first part of 1946 until March 17 when a resurgence of strong lava emission was marked by the reopening of the Ahuán vent (Kennedy, 1946), becoming less copious in June and more copious in July and August (J. A. Hernández V., field notes). About September 11, 1946, a new Mesa de los Hornitos vent took over from the Ahuán vent, building up to a climax of fountaining in mid-October and continuing with decreasing volume through the remainder of 1946 (Wilcox, 1947a).

On January 14, 1947, with the further decline of the Mesa de los Hornitos vent, "Puertecito," a new vent, opened at the immediate southwest base of the cone and furnished moderate amounts of lava



Grid ticks correspond to grid of figure 97

FIGURE 96.—Area covered by lavas of Parícutin volcano to end of 1944.

until it finally ceased on March 2. Meanwhile, on January 19 lava began to issue from the northeast base (the new Sapichu or Nuevo Juatito vent) for the first time since January 1944. The flow was sluggish at first; but with the closing of the Puertecito vent on the opposite side of the cone March 2, the new Sapichu vent effusion became appreciable. On August 11 fountaining occurred from the new Sapichu vent, and on August 14 the Puertecito vent reopened and remained strongly active while the Sapichu vent became weak, finally ceasing on October 1. On September 1 the old Ahuán vent was rejuvenated and took over the major portion of lava emission, which continued in moderate to large amounts until the end of 1947 (Wilcox, 1947b, 1948a, b; Wilcox and Shoup 1948). It was noted that the lava from the new Ahuán vent tended to pile up more around the vent and spread from the vent in broad lobes of much greater

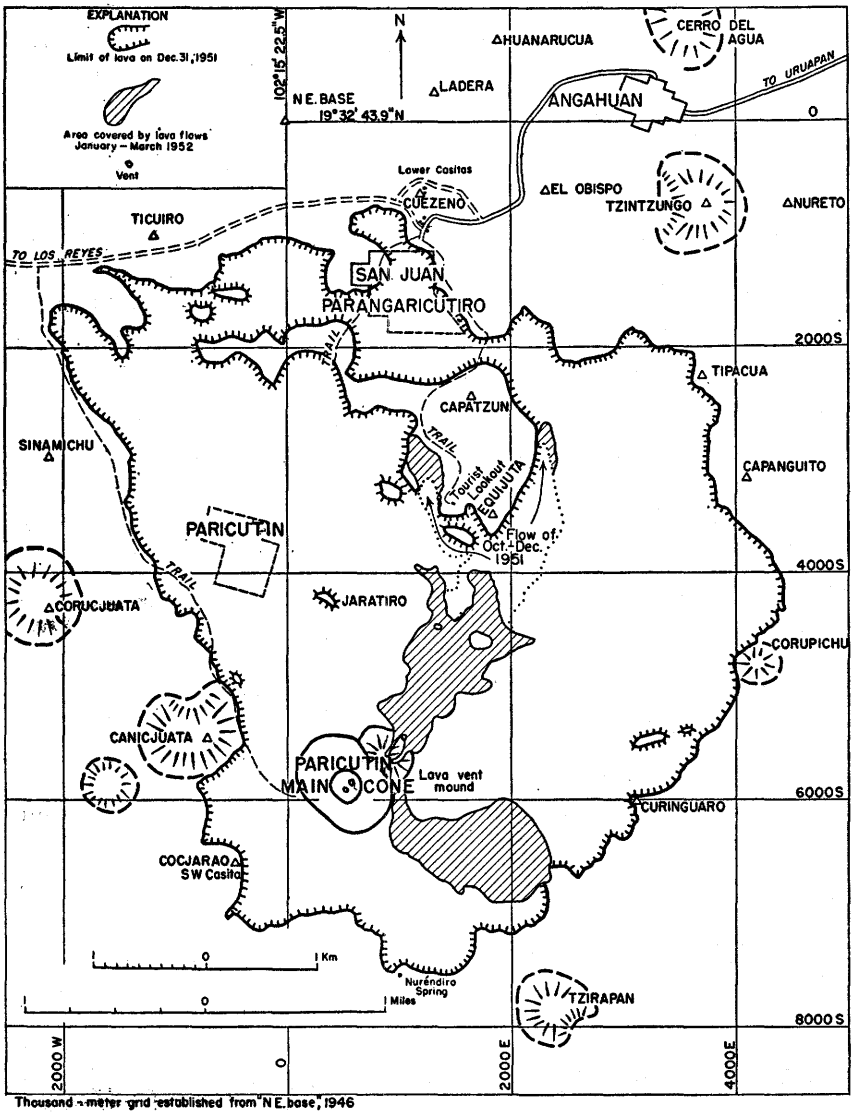


FIGURE 97.—Area covered by lavas of Parícutin volcano to end of 1952 (after Fries and Gutiérrez, 1954).

thickness than in previous flows (Wilcox and Shoup 1948, p. 79). This may have been due in part to the smaller gradients in the direction of this flow and in part to greater viscosity of the lava, which, it is found (fig. 100), had by this time reached a silica content of over 58 percent.

On February 7, 1948, the lava vent at the northeast base of the cone opened again, and by February 16 the Ahuán vent had closed. Thereafter, until final sudden cessation of lava activity of the volcano February 25, 1952, the effusion of lava was continuous from the northeast vent, (Fries and Gutiérrez, 1950a; 1950b, 1951a, 1951b, 1952a, 1952b, 1954). The rate of effusion varied from moderate to strong from February 1948 through January 1949 and was generally weak from the end of February 1949 to July 1949, increasing to moderate from July through December 1949. From January to June 1950 the effusion of lava was generally strong, with several brief periods of weak eruption of a few days duration. From June 20 to August 25 the eruption of lava was moderate, and from August 25 to October 15 it vacillated between strong, moderate, and weak at intervals of several days. Thereafter to the end of 1950, the eruption of lava was moderate except for the last 10 days when it varied between moderate and weak.

The variable behavior of lava effusion continued through January 1951, becoming predominantly large during the last half of February. The effusion of lava was very small from March 8 to 19, and thereafter to June 20 was moderate for the most part. The effusion of lava was large from June 21 to November 9, thereafter to the end of the year varied from small to large. During January and February the effusion of lava was moderate to large, ceasing altogether on February 25, 1952, just five days after the ninth birthday of the volcano.

A general chronology of the pyroclastic eruptions would be difficult, other than to say that the amount of pyroclastics erupted during the first couple of years was greater than subsequently and that the intensity varied greatly from both the short-term and long-term viewpoints. The almost complete cessation of pyroclastic eruption (but not vapor eruption) from the main cone during the active period of the Sapichu lava vent, October 18, 1943, to January 6, 1944, is notable. There were weeks-long periods of little pyroclastic activity during the latter part of 1945 and early 1946, mid-February to mid-March 1947, July 26–August 7, 1947, and mid-March to mid-June 1948. Subsequently, until the end of June 1951, the eruption of pyroclastics was weak for the most part, punctuated by brief periods of voluminous eruptions of ash and bombs and by spasmodic surges of pyroclastics and strong explosions of increasing frequency and intensity. From July through October 1951 the pyroclastic eruption was uniformly strong, becoming moderate for most of November and strong to very strong for December 1951 and January and early February 1952. After lava eruption ceased on February 25, only weak explosions occurred; and eruption of pyroclastics ceased on March 4, 1952.

The total areal extent of the new lava field at the end of the eruption, as shown on figure 97, is about 24.8 square kilometers (Fries and Gutiérrez, 1954). The total weight of rock material erupted, including both lava and pyroclastics, is computed by Fries (1953, p. 611) as about $3596 \times 10^6$ metric tons. Assuming an average specific gravity of 2.6 in the molten state, it would have occupied about 1.4 cubic kilometers in the Parícutin magma chamber.

In order to determine whether variations in atmospheric pressure might have some control on the variations of pyroclastic activity, a record of barometric pressure was kept at Cuzeño station, 5 kilometers north of Parícutin volcano starting in September 1946. No obvious correlation between atmospheric pressure and intensity of volcanic activity was noted. Likewise, there was no apparent correlation between the pyroclastic or lava activity and the variations in tide producing force, calculated by the U. S. Coast and Geodetic Survey for the vicinity of Parícutin volcano. (See eruptive diagrams in Wilcox, 1947a and b, 1948a and b; Wilcox and Shoup, 1948; Wilcox and Gutiérrez, 1948.)

## PETROGRAPHY

During the protracted eruption of Parícutin volcano, the petrographic character of successive ejecta changed from an olivine-bearing basaltic andesite to an orthopyroxene-bearing andesite, and this change was accompanied by a gradual change of chemical compositions. In the petrographic descriptions which follow, the megaphenocrysts will be discussed separately from the groundmasses, which include microphenocrysts, microlites, and glassy mesostasis.

The material erupted during 1943 and early 1944 is characterized by small numbers of olivine and plagioclase megaphenocrysts in a groundmass composed of plagioclase, olivine, clinopyroxene microphenocrysts (with or without orthopyroxene microphenocrysts) in a clear glass or microlite-charged glass mesostasis. The material erupted after the first part of 1944 is notably lacking in plagioclase megaphenocrysts, and until 1947 the only megaphenocrysts are olivine, lying in a groundmass of plagioclase, decreasing amounts of olivine and clinopyroxene microphenocrysts, and increasing amounts of orthopyroxene microphenocrysts in the glassy mesostasis. The material erupted after 1947 and until the end of 1950 is characterized by scattered orthopyroxene megaphenocrysts and, rarely, corroded olivine megaphenocrysts in a groundmass composed of plagioclase and orthopyroxene microphenocrysts and glassy mesostasis.

Petrographic descriptions of some of the lavas and bombs erupted from Parícutin volcano during 1943–45 have been given by Schmitter (1945, p. 127), Milton (1945), and Williams (1950, p. 256–265). Schmitter classed the rocks of 1943 as latitic olivine basalt ("basalto latitico de olivino"), while Milton regarded them as andesite of "basaltic habit." Williams (1950, p. 256) chose to call them basaltic andesites on the basis of low but positive *qz* values, shown by chemical analyses, and the presence of modal olivine. Because of the limited number of analyses at his disposal, Williams was led to characterize the ejecta of Parícutin as monotonously similar, with no evidence of serial trends. No detailed petrographic descriptions of material erupted since 1945 have been published, and the definite compositional trends have only been revealed as analyses on later erupted material have become available.

In the present study more than 125 specimens of lavas, bombs, and xenoliths of Parícutin volcano have been examined in hand specimen and in thin section. The dates of eruption of these specimens cover the period from 1943 through 1952—with unfortunate gaps during the first portion of 1946, for which specimens are not available, and during the first portion of 1948, specimens of which were lost in shipment. Optic angles and extinction angles were measured directly in thin section on the universal stage. Refractive indices, $nX'$, of plagioclase cleavage fragments were determined in immersion liquids with sodium light as were values of $nZ$ of some orthopyroxene cleavage fragments. Measurements of $nX$, $nY$, and $nZ$ of other orthopyroxene and of olivines were made using the method of Rosenfeld (1950). Compositions of individual minerals of the Parícutin lavas have been inferred from their optical properties, using $2V$ and $nZ$ of orthopyroxene (Winchell, 1951, fig. 283), refractive indices of olivine (Winchell, 1951, fig. 395), and extinction angles $X' \wedge 010_{max}$ and $X' \wedge 010 \perp a$ for plagioclase (Winchell, 1951, figs. 148 and 176 respectively).

Attention should be drawn here, however, to the different compositions that can be inferred by applying the same optical data to curves compiled by different authors. The orthopyroxene of specimen W–48–5 (see description below) was found to have (negative) $2V=80°$ and $nZ=1.695$. Applied to Winchell's (1951) figure 283, both $2V$ and $nZ$ lead to an inferred composition of $En_{75}$. Applied to Kennedy's (1947) figure 3 (derived largely from Hess and Phillips, 1940), $2V$ leads to an inferred composition of $En_{84}$ while $nZ$ leads to an inferred composition of $En_{77}$. This is in spite of the apparent excellence of the data of Hess and Phillips for the particular orthopyroxenes that they investigated. The curves of Winchell are used in the present investigation simply because they seem to give consistent values of composition for both $2V$ and $nZ$. If the values are in error it is probable that the error of most are in the same direction and of similar magnitude, so that at least the relative differences in composition between the orthopyroxenes of the Parícutin lavas can be depended upon.

Compositions of plagioclases of volcanic rocks, inferred from conventional extinction angle curves, may be in error by several percent if one gives credence to the existence of a separate set of optical properties for high-temperature plagioclases, as suggested by the work of Köhler (1949) and others. The original complete curves of Rittmann (1929) for extinction angles in different orientations were computed from the optical data on plutonic plagioclases, that is, plagioclases that had cooled very slowly and had low-temperature optical properties. Using the complete Rittmann procedure, the writer in fact has found that curves of extinction angles of particular Parícutin plagioclases do not fit in the family of complete curves published by Rittmann. In view of the disagreement still existing concerning the optical properties of volcanic and plutonic plagioclases, the conventional "low-temperature" curves of Winchell (1951, fig. 148) have been used here, recognizing that the anorthite-contents thus inferred are on the order of 10 percent greater than those to be inferred from the "high-temperature" curves recently compiled by Tröger (1952, p. 113).

The volume percentages of megaphenocrysts, measured by the Chayes (1949) point-counting method, are given in table 1 for all but five of the analyzed specimens and for a few additional specimens. The results are graphed according to dates of eruption in figure 98. Because in some specimens there is no sharp demarcation in size-frequency distribution between large and small phenocrysts, megaphenocrysts have been arbitrarily defined as crystals larger than 0.3 millimeter in longest dimension, while microphenocrysts are defined as those crystals ranging in size from 0.3 millimeter down to 0.03 millimeter, the lower limit depending somewhat on morphology. The relative abundance of microphenocrysts and microlites of plagioclase, olivine, orthopyroxene, and clinopyroxene, estimated by eye in all the thin sections available, are graphed according to dates of eruption in figure 99. Where two or more specimens are so close in date of eruption that they could not be shown separately, the average of the results is graphed for the group of specimens of that date. In the following paragraphs the petrography will first be described for several individual specimens, then for the individual constituents through the series. This will be followed by a description of representative xenoliths and a discussion of the mutual effects between xenolith and enclosing lava.

TABLE 1.—*Volume percentages of megaphenocrysts, and groundmass (vesicle-free) and of vesicles in Parícutin lavas*

| Analysis number | Specimen number | Date Erupted | Megaphenocrysts | | | | Ground-mass | Vesicles |
|---|---|---|---|---|---|---|---|---|
| | | | Olivine | Ortho-pyrox-ene | Clino-pyrox-ene | Plagio-clase | | |
| 1 | | Feb. 22, 1943 | 2.2 | 0 | 0 | 1.1 | 96.7 | 17.7 |
| 4 | 11-16-1 | Apr.(?) 1944 | 3.3 | 0 | 0 | 0 | 96.7 | 2.0 |
| 6 | 11-29-1 | Nov. 1945 | 2.5 | 0 | 0 | 0 | 97.5 | 19.5 |
| 7 | 11-26-2 | Nov | 3.6 | 0 | 0 | 0 | 96.4 | 17.3 |
| 8 | 12-7-1 | Dec | 3.2 | 0 | 0 | 0 | 96.8 | 9.5 |
| 9 | 12-3-1 | Dec | 3.3 | 0 | 0 | 0 | 96.7 | 26.6 |
| 10 | 12-19-1 | Dec | 3.0 | 0 | 0 | 0 | 97.0 | 20.5 |
| | 2-7-1 | Feb. 1946 | 4.0 | 0 | 0 | 0 | 96.0 | 14.5 |
| 11 | W-46-27 | Sept | 2.6 | tr | 0 | 0 | 97.4 | 7.3 |
| | W-47-6 | Feb. 1947 | 2.5 | 0 | 0 | 0 | 97.5 | 11.8 |
| 12 | W-47-9 | May | 4.5 | 0 | 0 | 0 | 95.5 | 24.7 |
| 13 | W-47-14 | June | 3.5 | .1 | 0 | 0 | 96.4 | 15.1 |
| 14 | W-47-19 | Sept | 2.3 | .7 | 0 | .3 | 96.7 | 5.7 |
| 15 | W-47-30 | Nov | 1.8 | tr | 0 | 0 | 98.2 | 30.8 |
| | W-47-31 | Dec | 1.7 | 0 | 0 | 0 | 98.3 | 15.0 |
| 16 | W-48-5 | Aug. 1948 | .9 | .7 | 0 | 0 | 98.4 | 14.0 |
| 17 | FP-5-49 | May 1949 | .2 | 1.4 | 0 | 0 | 98.4 | 23.5 |
| 18 | FP-20-49 | Dec | .6 | 1.3 | 0 | 0 | 98.1 | 12.0 |
| 19 | FP-20-50 | Sept. 1950 | 0 | 1.2 | 0 | .1 | 98.7 | 29.1 |
| | FP-55-50 | Dec | .3 | 2.4 | 0 | 0 | 97.3 | 14.0 |
| 22 | FP-16-52 | Feb. 1952 | .3 | .7 | 0 | .1 | 98.9 | 18.2 |

## REPRESENTATIVE LAVA SPECIMENS

The thin section of the specimen of lava of February 22, 1943 (analysis 1, table 2), collected by G. A. Cooper and chemically analyzed by Charles Milton (1945), shows 2.2 percent by volume of euhedral olivine megaphenocrysts up to 0.5 millimeter in diameter and 1.1 percent by volume of plagioclase megaphenocrysts up to 0.4 millimeter in length. The hand specimen of this thin section was not available to the writer. An olivine megaphenocryst from lava erupted in March 1943 (specimen 51–W–18), however, showed the following refractive indices:

$nX = 1.667 \pm 0.002$
$nY = 1.691$ to $1.693 \pm 0.002$
$nZ = 1.713 \pm 0.003$
Inferred composition is $Fo_{82-79}$.

Extinction angles $X' \wedge 010 \perp a$ of four plagioclase megaphenocrysts range from 39° to 36° with slight progressive normal zoning. The inferred average range of composition is $An_{75-72}$. Groundmass is composed of abundant microphenocrysts of plagioclase, showing slight progressive normal zoning (inferred average range $An_{74-68}$), many euhedral microphenocrysts, and grains of olivine (inferred composition near $Fo_{70}$ by $2V$), and abundant microlites of orthopyroxene (?), chiefly as stubby prisms up to 0.005 millimeter length in a mesostasis of brown glass composing about 5 percent of the volume of the rock.

A lava erupted in March 1943 (Instituto de Geología de México thin section labeled "Lava de Marzo 1943") has many euhedral megaphenocrysts of olivine up to 0.8 millimeter in diameter and many lath-shaped megaphenocrysts of plagioclase from 0.3 to 0.6 millimeter in length. (See pl. 10, fig. 1.) Judging from the descriptions by Schmitter (1945), the occurrence of megaphenocrysts of plagioclase is not uncommon in the earliest lavas. The groundmass of this specimen is composed of abundant plagioclase; many stubby prisms of clinopyroxene (augitic?), some as long as 0.15 millimeter; microlites of orthopyroxene (?); dendrites and skeletons of opaque oxide; and innumerable tiny bubbles in a glassy mesostasis, which is estimated to compose about 25 percent of the volume of the rock.

A specimen, estimated to have been erupted about April 1944 and collected by K. B. Krauskopf from the middle reaches of the great San Juan flow (specimen 11–16–1, analysis 4, table 2), is dense black with scattered olivine phenocrysts. In thin section the texture is porphyritic intersertal. Olivine megaphenocrysts compose 3.3 percent by volume of the rock and range up to 1.3 millimeter in length. They are generally euhedral but show minor embayment and attachments of (or reaction to form) small orthopyroxene crystals. Plagioclase megaphenocrysts are rare; one embayed and internally corroded fragment of plagioclase (xenocryst?) was found in the section. In the groundmass, plagioclase microphenocrysts predominate. Most are less than 0.2 millimeter in length and not well terminated. Extinction angles $X \wedge 010 \perp a$ of the central portions of 10 crystals ranged from 37° to 34°, from which an average composition of $An_{68}$ is inferred. Zoning in most crystals is normal-progressive, being much more marked in the thin rims which commonly range in composition down to $An_{50}$ and less. Orthopyroxene microphenocrysts are common as stubby prisms up to 0.1 millimeter in length, showing slightly higher interference color than in the orthopyroxene of most of the Parícutin lavas. Optic angles were measured in two crystals as (negative) $2V=70°$ and 68°, from which compositions of $En_{67}$ and $En_{65}$ are inferred. A lesser number of elongate clinopyroxene crystals up to 0.6 millimeter in length are present; none lend themselves to determination of optic angles. Many polyhedrons (cubes?) of opaque oxide up to 0.05 millimeter are present and are presumed to be magnetite. Also present in the groundmass are scattered irregularly shaped grains of olivine, usually with adhering orthopyroxene crystals. Microlites of orthopyroxene (?), clinopyroxene (?), and dendrites of opaque oxide are distributed through a brown translucent glassy mesostasis which composes about 10 percent of the volume of the rock.

TABLE 2.—*Analyses of lavas from Parícutin volcano, Mexico*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bulk Analyses** | | | | | | | | | | | |
| $SiO_2$ | 55.04 | 54.88 | 55.51 | 55.21 | 55.59 | 56.41 | 56.15 | 56.48 | 56.41 | 56.61 | 56.13 |
| $Al_2O_3$ | 18.82 | 18.38 | 18.19 | 17.94 | 17.72 | 17.67 | 17.57 | 17.57 | 17.60 | 17.61 | 17.34 |
| $Fe_2O_3$ | 1.92 | 1.31 | 1.63 | 1.60 | 1.33 | 1.39 | 1.80 | 1.63 | 1.67 | 1.45 | 1.74 |
| FeO | 5.69 | 5.97 | 5.38 | 5.96 | 5.99 | 5.40 | 5.08 | 5.18 | 5.18 | 5.35 | 5.42 |
| MgO | 5.68 | 5.57 | 5.31 | 5.37 | 5.60 | 5.66 | 5.68 | 5.56 | 5.62 | 5.64 | 5.58 |
| CaO | 7.17 | 7.40 | 7.19 | 6.98 | 6.99 | 6.89 | 6.95 | 6.95 | 6.90 | 6.89 | 6.99 |
| $Na_2O$ | 3.88 | 3.88 | 3.92 | 3.87 | 4.00 | 3.87 | 3.85 | 3.70 | 3.81 | 3.84 | 3.79 |
| $K_2O$ | .85 | .86 | 1.10 | 1.26 | 1.13 | 1.19 | 1.18 | 1.34 | 1.20 | 1.21 | 1.30 |
| $H_2O+$ | .16 | .13 | .08 | .05 | .03 | .04 | .04 | .08 | .05 | .05 | .20 |
| $H_2O-$ | | .05 | .01 | .01 | .04 | .03 | .04 | .00 | .00 | .03 | .06 |
| $CO_2$ | n. d. | n. d. | n. d. | n. d. | n. d. | n. d. | n. d. | n. d. | n. d. | n. d. | .06 |
| $TiO_2$ | .94 | .95 | .97 | 1.08 | 1.05 | .93 | .95 | .94 | .93 | .93 | 1.02 |
| $P_2O_5$ | .21 | .29 | .31 | .41 | .36 | .30 | .30 | .37 | .31 | .30 | .36 |
| MnO | .07 | .13 | .12 | .13 | .13 | .12 | .12 | .11 | .12 | .11 | .12 |
| Total | [1] 100.51 | 99.80 | 99.72 | 99.87 | 99.96 | 99.90 | 99.71 | 99.91 | 99.80 | 100.02 | 100.11 |
| **Normative minerals** | | | | | | | | | | | |
| Q | 3.47 | 2.40 | 3.54 | 3.30 | 3.46 | 4.62 | 4.86 | 5.63 | 5.59 | 4.86 | 4.87 |
| Or | 4.99 | 5.56 | 6.67 | 7.77 | 6.62 | 7.22 | 7.23 | 7.77 | 6.69 | 7.23 | 7.80 |
| Ab | 32.40 | 33.01 | 33.52 | 32.44 | 33.82 | 32.45 | 32.49 | 31.39 | 32.04 | 32.46 | 32.04 |
| An | 31.32 | 30.02 | 28.63 | 27.76 | 26.78 | 27.48 | 27.24 | 27.48 | 27.87 | 27.21 | 26.48 |
| Wo | 1.04 | 2.20 | 2.32 | 1.86 | 2.18 | 2.09 | 2.32 | 1.86 | 1.98 | 2.20 | 2.79 |
| En | 14.16 | 14.00 | 13.28 | 13.38 | 13.91 | 14.19 | 14.20 | 13.88 | 14.13 | 14.10 | 13.93 |
| Fs | 7.37 | 8.58 | 7.26 | 8.04 | 8.26 | 7.52 | 6.60 | 6.86 | 7.02 | 7.52 | 6.88 |
| Mt | 2.77 | 1.86 | 2.32 | 2.32 | 1.85 | 2.09 | 2.55 | 2.32 | 2.33 | 2.09 | 2.56 |
| Il | 1.82 | 1.67 | 1.82 | 2.13 | 2.12 | 1.67 | 1.82 | 1.82 | 1.68 | 1.67 | 1.98 |
| Ap | .67 | .67 | .67 | 1.01 | 1.00 | .67 | .67 | 1.01 | .67 | .67 | .67 |
| **Calculated groundmass compositions** | | | | | | | | | | | |
| $SiO_2$ | 55.53 | -------- | -------- | 56.12 | -------- | 57.20 | 57.30 | 57.42 | 57.45 | 57.42 | 56.94 |
| $Al_2O_3$ | 19.22 | -------- | -------- | 18.80 | -------- | 18.34 | 18.53 | 18.39 | 18.46 | 18.36 | 18.02 |
| Total Fe as FeO | 7.15 | -------- | -------- | 6.92 | -------- | 6.24 | 6.15 | 6.15 | 6.16 | 6.18 | 6.60 |
| MgO | 4.66 | -------- | -------- | 3.76 | -------- | 4.41 | 3.94 | 4.01 | 4.02 | 4.18 | 4.34 |
| CaO | 7.29 | -------- | -------- | 7.31 | -------- | 7.15 | 7.33 | 7.27 | 7.24 | 7.18 | 7.26 |
| $Na_2O$ | 4.00 | -------- | -------- | 4.05 | -------- | 4.02 | 4.06 | 3.87 | 4.00 | 4.01 | 3.93 |
| $K_2O$ | .88 | -------- | -------- | 1.32 | -------- | 1.23 | 1.25 | 1.40 | 1.26 | 1.26 | 1.36 |
| $TiO_2$ | .98 | -------- | -------- | 1.13 | -------- | .96 | 1.01 | .98 | .97 | .97 | 1.06 |
| $P_2O_5$ | .22 | -------- | -------- | .43 | -------- | .31 | .31 | .39 | .32 | .31 | .37 |
| MnO | .07 | -------- | -------- | .14 | -------- | .12 | .12 | .11 | .12 | .11 | .12 |
| Total | 100.00 | -------- | -------- | 99.98 | -------- | 99.98 | 100.00 | 99.99 | 100.00 | 99.98 | 100.00 |

[1] Includes 0.04 S and 0.06 BaO.

*Data on specimens analysed*

| Analysis | Specimen | Date erupted | Collector | Analyst |
|---|---|---|---|---|
| 1 | | Feb. 22, 1943 | C. A. Cooper | Charles Milton (1945). |
| 2 | USNM 108058 | Mar. 1943 | W. H. Foshag | E. Chadbourn (Williams, 1950). |
| 3 | USNM 108073 | Nov. 1943 | do | Do. |
| 4 | 11-16-1 | Apr. (?) 1944 | K. Krauskopf | James Kerr. |
| 5 | USNM 108100 | Nov. 1944 | W. H. Foshag | E. Chadbourn (Williams, 1950). |
| 6 | 11-29-1 | Nov. 1945 | K. Krauskopf | James Kerr. |
| 7 | 11-26-2 | Nov. 21, 1945 | do | Do. |
| 8 | 12-7-1 | Dec. 1945 | do | Do. |
| 9 | 12-3-1 | do | do | Do. |
| 10 | 12-19-1 | do | do | Do. |
| 11 | W-46-27 | Sept. 18, 1946 | J. A. Herñandez V. | H. Hyman. |

TABLE 2.—*Analyses of lavas from Parícutin volcano, Mexico*—Continued

| 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Bulk Analyses—Continued** | | | | | | | | | | |
| 57.05 | 57.63 | 58.13 | 58.39 | 59.09 | 59.41 | 59.77 | 59.93 | 60.24 | 60.38 | 60.07 |
| 17.27 | 17.50 | 17.59 | 17.78 | 17.55 | 17.30 | 17.29 | 17.31 | 17.30 | 17.27 | 17.28 |
| 1.42 | 1.38 | 1.27 | 1.87 | 2.04 | 1.57 | 1.21 | 1.23 | 1.19 | 1.10 | 1.37 |
| 5.21 | 5.12 | 5.20 | 4.51 | 4.27 | 4.78 | 4.95 | 4.95 | 4.59 | 4.66 | 4.39 |
| 5.64 | 5.16 | 4.55 | 4.03 | 4.03 | 3.81 | 3.72 | 3.55 | 3.55 | 3.59 | 3.73 |
| 6.94 | 6.77 | 6.72 | 6.75 | 6.46 | 6.36 | 6.28 | 6.21 | 6.14 | 6.16 | 6.16 |
| 3.71 | 3.71 | 3.79 | 3.86 | 3.92 | 3.71 | 3.74 | 3.73 | 4.01 | 3.89 | 4.00 |
| 1.23 | 1.38 | 1.41 | 1.30 | 1.50 | 1.67 | 1.67 | 1.72 | 1.66 | 1.69 | 1.67 |
| .17 | .04 | .10 | .11 | .08 | .12 | .12 | .10 | .04 | .05 | .03 |
| .02 | .02 | .03 | .01 | .03 | .00 | .00 | .00 | .04 | .05 | .05 |
| .02 | .01 | .01 | .01 | .00 | .02 | .00 | .01 | .00 | .00 | .01 |
| .89 | .86 | .84 | .86 | .78 | .84 | .83 | .83 | .80 | .80 | .81 |
| .29 | .29 | .30 | .30 | .30 | .31 | .31 | .30 | .29 | .28 | .28 |
| .12 | .12 | .11 | .12 | .11 | .11 | .11 | .11 | .10 | .10 | .10 |
| 99.98 | 99.99 | 100.05 | 99.90 | 100.16 | 100.01 | 100.00 | 99.98 | 99.95 | 100.01 | 99.95 |
| **Normative minerals—Continued** | | | | | | | | | | |
| 6.30 | 7.01 | 7.59 | 9.71 | 10.13 | 10.77 | 10.80 | 11.28 | 10.68 | 11.58 | 10.51 |
| 7.23 | 8.32 | 8.32 | 7.77 | 8.89 | 10.04 | 10.01 | 10.01 | 10.02 | 10.01 | 10.02 |
| 31.42 | 31.37 | 32.46 | 32.44 | 32.98 | 31.52 | 31.96 | 31.96 | 34.07 | 32.49 | 34.10 |
| 26.95 | 26.91 | 26.62 | 27.47 | 25.82 | 25.64 | 25.30 | 25.30 | 24.20 | 25.02 | 24.22 |
| 2.44 | 2.09 | 2.21 | 1.86 | 1.86 | 1.86 | 1.74 | 1.63 | 1.97 | 1.63 | 1.97 |
| 14.10 | 12.88 | 11.38 | 10.09 | 10.09 | 9.52 | 9.30 | 8.90 | 8.91 | 9.00 | 9.31 |
| 7.13 | 6.99 | 7.37 | 5.54 | 5.02 | 6.36 | 6.86 | 6.86 | 6.34 | 6.47 | 5.82 |
| 2.09 | 2.09 | 1.86 | 2.78 | 3.02 | 2.10 | 1.86 | 1.86 | 1.62 | 1.62 | 1.86 |
| 1.67 | 1.67 | 1.52 | 1.67 | 1.52 | 1.52 | 1.52 | 1.52 | 1.52 | 1.52 | 1.52 |
| .67 | .67 | .67 | .67 | .67 | .67 | .67 | .67 | .67 | .67 | .67 |
| **Calculated groundmass compositions—Continued** | | | | | | | | | | |
| 58.37 | 58.65 | 58.91 | 59.10 | 59.44 | 59.71 | 60.16 | 60.16 | -------- | -------- | -------- |
| 18.40 | 18.40 | 18.29 | 18.28 | 17.95 | 17.71 | 17.76 | 17.60 | -------- | -------- | -------- |
| | | | | | | | | | | |
| 5.74 | 5.76 | 5.89 | 5.92 | 5.87 | 5.99 | 5.77 | 5.93 | -------- | -------- | -------- |
| 3.42 | 3.39 | 3.19 | 3.14 | 3.38 | 3.29 | 3.01 | 3.19 | -------- | -------- | -------- |
| 7.40 | 7.11 | 6.98 | 6.94 | 6.61 | 6.51 | 6.46 | 6.32 | -------- | -------- | -------- |
| 3.95 | 3.90 | 3.95 | 3.97 | 4.01 | 3.80 | 3.84 | 3.79 | -------- | -------- | -------- |
| 1.31 | 1.45 | 1.47 | 1.34 | 1.53 | 1.70 | 1.71 | 1.75 | -------- | -------- | -------- |
| .95 | .90 | .88 | .88 | .80 | .86 | .85 | .85 | -------- | -------- | -------- |
| .31 | .30 | .31 | .31 | .31 | .32 | .32 | .31 | -------- | -------- | -------- |
| .13 | .12 | .11 | .12 | .11 | .11 | .11 | .11 | -------- | -------- | -------- |
| 99.98 | 99.98 | 99.98 | 100.00 | 100.01 | 100.00 | 99.99 | 100.01 | -------- | -------- | -------- |

*Data on specimens analysed*—Continued

| Analysis | Specimen | Date erupted | Collector | Analyst |
|---|---|---|---|---|
| 12 | W-47-9 | Apr. 9, 1947 | J. A. Herñandez V. | H. HYman |
| 13 | W-47-14 | June 10, 1947 | C. Gutiérrez | Do. |
| 14 | W-47-19 | Sept. 5, 1947 | S. Shoup O. | Do. |
| 15 | W-47-30 | Nov. 1947 | R. E. Wilcox | Do. |
| 16 | W-48-5 | Aug. 1948 | do | Do. |
| 17 | FP-5-49 | May 19, 1949 | C. Fries, Jr | Do. |
| 18 | FP-20-49 | Dec. 13, 1949 | do | Do. |
| 19 | FP-20-50 | Sept. 1, 1950 | do | Do. |
| 20 | FP-5-51 | May 1951 | do | Lucile Tarrant. |
| 21 | FP-13-51 | Nov. 1951 | C. Gutiérrez | Do. |
| 22 | FP-16-52 | Feb. 25, 1952 | C. Fries, Jr | Do. |

TABLE 3.—*Analyses of xenoliths from Parícutin volcano, Mexico*

| Bulk Analyses | | | | | Normative minerals | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | X-1 | X-2 | X-3 | X-4 | | X-1 | X-2 | X-3 | X-4 |
| $SiO_2$ | 70.88 | 71.99 | 71.10 | 75.95 | Q | 26.79 | 32.27 | 29.97 | 33.02 |
| $Al_2O_3$ | 14.27 | 15.95 | 14.31 | 13.51 | Or | 21.75 | 14.43 | 22.22 | 27.82 |
| $Fe_2O_3$ | 1.52 | .68 | 1.43 | .25 | Ab | 35.75 | 34.51 | 27.22 | 33.03 |
| FeO | 1.53 | 1.22 | 1.63 | .27 | An | 7.53 | 11.38 | 13.33 | 5.28 |
| MgO | 1.17 | .71 | 1.14 | .05 | C | .71 | 2.44 | ------ | ------ |
| CaO | 1.65 | 2.49 | 2.88 | 1.05 | En | 2.91 | 1.80 | 2.90 | .10 |
| $Na_2O$ | 4.18 | 4.03 | 3.20 | 3.90 | Fs | 2.52 | 1.45 | 1.19 | .13 |
| $K_2O$ | 3.64 | 2.43 | 3.76 | 4.74 | Mt | .93 | .93 | 2.09 | .46 |
| $H_2O+$ | .11 | .13 | .07 | .13 | Il | .76 | .46 | .76 | .15 |
| $H_2O-$ | .05 | .02 | .01 | 0 | Ap | .34 | .34 | .34 | ------ |
| $CO_2$ | .02 | .01 | 0 | 0 | | | | | |
| $TiO_2$ | .36 | .21 | .37 | .04 | | | | | |
| $P_2O_5$ | .08 | .09 | .07 | .02 | | | | | |
| MnO | .05 | .05 | .05 | .03 | | | | | |
| Total | [1] 99.64 | 100.01 | 100.02 | 99.94 | | | | | |

[1] Includes 0.26S.

*Data on specimens analyzed*

| Analysis | Specimen | Date erupted | Collector | Analyst |
|---|---|---|---|---|
| X-1 | 51-W-1 | May 1943 | F. H. Pough | E. Engleman. |
| X-2 | 51-W-5 | 1943 | Inst. de Geol. de México | Do. |
| X-3 | 51-W-9 | 1944-45 | do | Do. |
| X-4 | 51-W-8 | 1944-45 | do | Do. |

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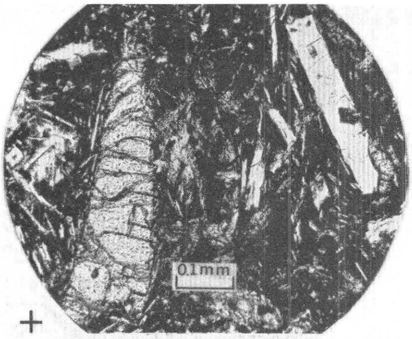
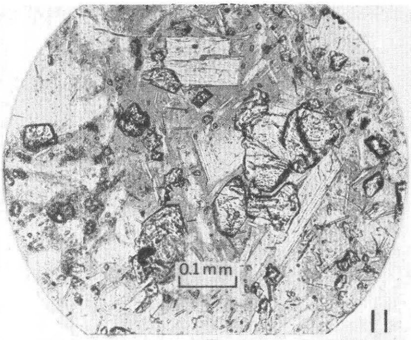
## PLATE 10

FIGURE 1. Lava erupted March 1943 (Instituto de Geología de Méxcio), thin section showing megaphenocrysts of plagioclase and olivine. Crossed nicols.

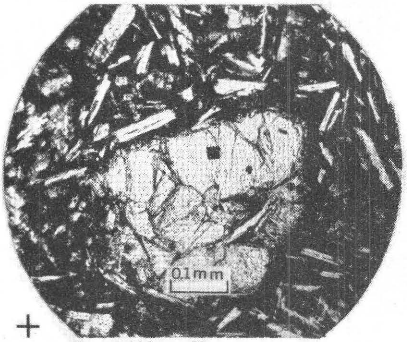
2. Pumice fragment erupted April 1944 (Instituto de Geología de México), thin section showing microphenocrysts of olivine and plagioclase and microlites of olivine and clinopyroxene (rods) in clear glass. Plane polarized light.
3. Lava erupted April 9, 1947 (analysis 12, table 2), showing olivine megaphenocryst with thin reaction rim of fine-grained orthopyroxene. Crossed nicols.
4. Lava erupted September 1950 (analysis 19, table 2), showing orthopyroxene megaphenocryst cluster. Plane polarized light.
5. Lava erupted February 1952 (analysis 22, table 2), showing orthopyroxene and plagioclase microphenocrysts in clear glass. Plane polarized light.
6. Lava erupted June 1947 (analysis 13, table 2), showing clinopyroxene flanking plates and extensions. Plane polarized light.



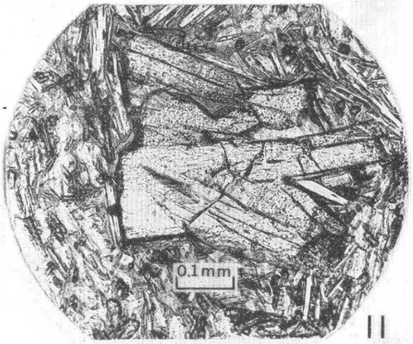
1



2



3



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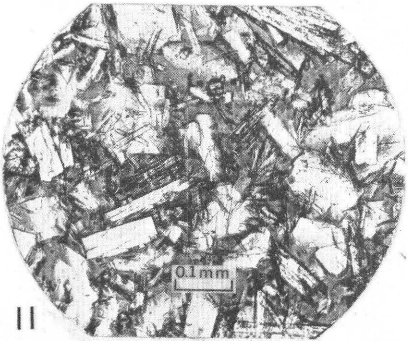
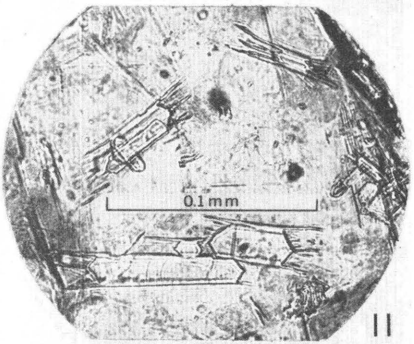
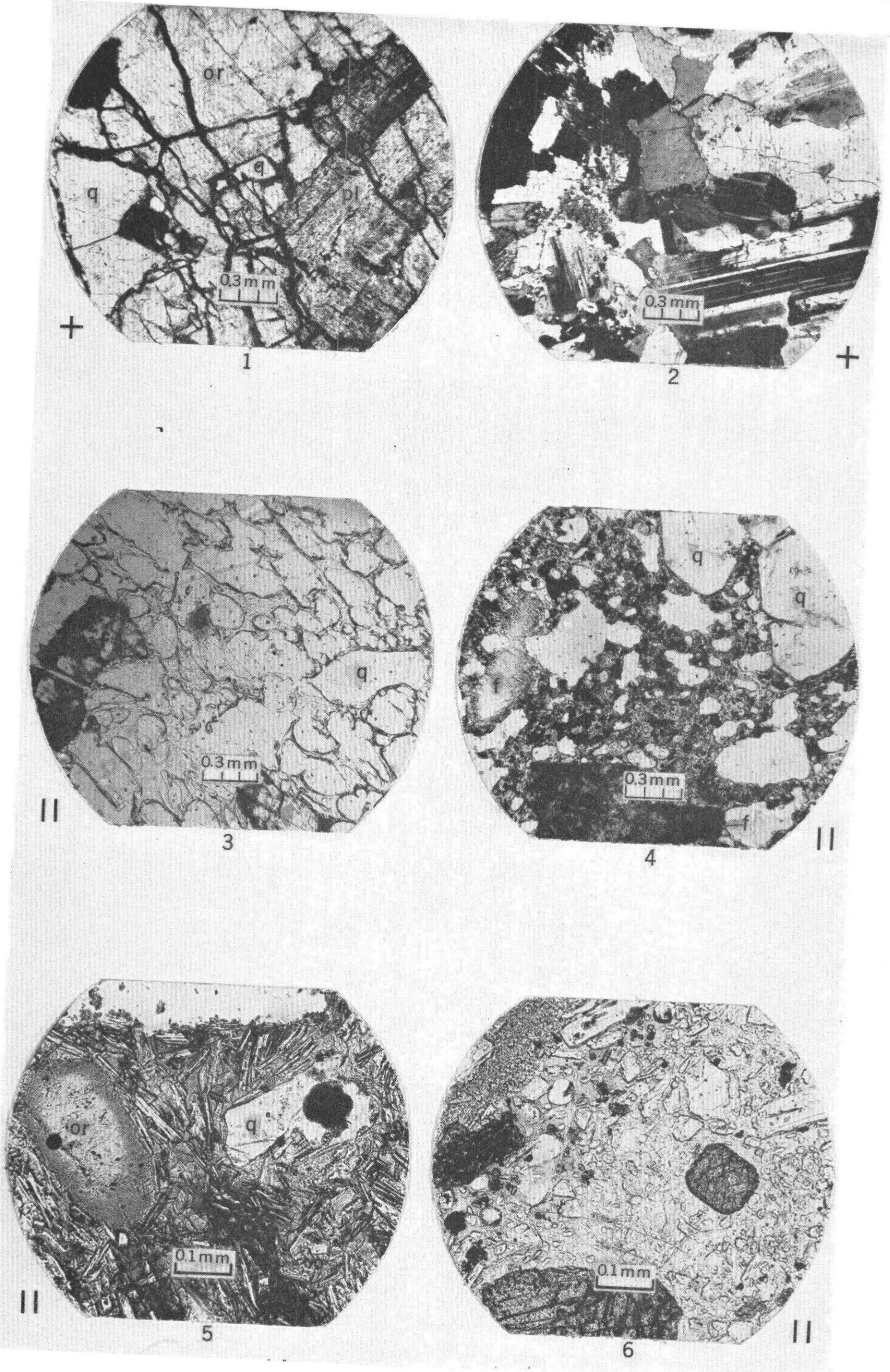


5



6

PHOTOMICROGRAPHS OF LAVAS AND PUMICE OF PARÍCUTIN VOLCANO



PHOTOMICROGRAPHS OF PARÍCUTIN XENOLITHS AND GRANODIORITE

Lava that issued from the northeast lava vent in May 1947 (Specimen W–47–9, analysis 12, table 2) is quite vesicular and contains 4.5 percent by volume of olivine megaphenocrysts ranging up to 0.8 millimeter in diameter, showing corroded outlines and carrying coronas of small orthopyroxene crystals (pl. 10, fig. 3). Refractive indices determined on cleavage fragments of olivine megaphenocrysts showed

$nX=1.675$
$nY=1.695$
$nZ=$approximately $1.712$,

corresponding to a composition of about $Fo_{80}$. No plagioclase megaphenocrysts are present. The groundmass consists of abundant plagioclase laths up to 0.25 millimeter in length, abundant orthopyroxene prisms up to 0.20 millimeter in length, a moderate number of clinopyroxene needles, scattered grains of olivine (rimmed with orthopyroxene), and dust-size, opaque oxide in a cloudy brown glass mesostasis which composes about 25 percent of the volume of the rock. Centers of groundmass plagioclase show $X'\wedge010$ maximum, ranging from 35° to 38° (implying $An_{60}$ to $An_{66}$) and rims range from 25° to 35° ($An_{44}$ to $An_{60}$). Three groundmass crystals of orthopyroxene have optic angles (negative) $2V=72°$ to $75°$ (implying $En_{69}$ to $En_{71}$).

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## PLATE 11

FIGURE 1. Quartz monzonite xenolith erupted May 1943 (analysis X–1, table 3) showing orthoclase (*or*), plagioclase (*pl*), and quartz (*q*) with black glass in fractures and along grain boundaries. Crossed nicols.

2. Granodiorite (specimen FP–20–52) from outcrop area 30 kilometers southeast of Parícutin volcano.

3. Frothy xenolith erupted 1943 (specimen collected by Instituto de Geología de México, Wilcox 51–W–4), showing quartz (*q*) and feldspar (*f*) and glass. Plane polarized light.

4. Vesicular xenolith (pyroclastic?) erupted in 1943 (specimen collected by Instituto de Geología de México, Wilcox 51–W–6), showing quartz (*q*) and feldspar (*f*) phenocrysts in inflated groundmass of quartz, feldspar, and glass. Plane polarized light.

5. Transition zone between xenolith and lava erupted October 1949 (specimen FP–11–49), showing quartz (*q*) and fritted orthoclase (*or*) xenocrysts in transitional glass groundmass containing plagioclase and orthopyroxene microphenocrysts and microlites. Plane polarized light.

6. Glassy xenolith erupted July 1945 (collected by F. H. Pough, Wilcox specimen 51–W–2), showing phenocrysts and fragments of orthopyroxene (about $En_{77}$) and plagioclase ($An_{60-64}$) in salic glass. Plane polarized light.

A specimen of lava, issued from the northeast lava vent on June 10, 1947 (specimen W-47-14, analysis 13, table 2), has a porphyritic intersertal texture with about 15 percent by volume of vesicles and 10–15 percent by volume of clear brown glass mesostasis. There is 3.5 percent olivine megaphenocrysts up to 1.2 millimeter diameter, somewhat corroded and carrying fine-grained orthopyroxene rims, and 0.1 percent by volume of orthopyroxene megaphenocrysts. Abundant microphenocrysts of plagioclase and orthopyroxene stand out clearly in the glass base. There are a few independent microlitic needles of clinopyroxene and many outgrowths and overgrowths of microlitic clinopyroxene on orthopyroxene microphenocrysts (pl. 10, fig. 6). Scattered cubes of opaque oxide up to 0.02 millimeter occur in the olivine crystals but are rare in the groundmass.

Lava of November 1947 from the active front of the lava flow issuing from the southwestern vent (specimen W-47-30, analysis 15, table 2) is quite vesicular, and olivine megaphenocrysts compose 1.8 percent by volume of the rock (vesicle-free). The olivine occurs as fractured and corroded crystals up to 1.5 millimeter diameter which carry coronas of fine-grained orthopyroxene. No megaphenocrysts of plagioclase or orthopyroxene were observed. The groundmass consists of abundant plagioclase laths and tablets up to 0.15 millimeter in length, abundant prisms of orthopyroxene up to 0.1 millimeter in length, and occasional ragged needles of clinopyroxene (also found as flanking plates on some orthopyroxene prisms). Opaque oxide crystals adhere to the clinopyroxene and are scattered through a slightly cloudy, brown glass basis, composing about 35 percent of the volume of the rock. Centers of groundmass plagioclase show $X' \wedge 010_{max} = 35°$ to $40°$ ($An_{60}$ to $An_{70}$). Determinations of optic angles of groundmass orthopyroxene showed a range of (negative) $2V = 70°$ to $79°$ ($En_{66}$ to $En_{74}$).

A specimen erupted in September 1948 (specimen W-48-5, analysis 16, table 2) is moderately vesicular and contains 0.9 percent of olivine megaphenocrysts and 0.7 percent by volume (of vesicle-free rock) of orthopyroxene megaphenocrysts. The olivine megaphenocrysts, ranging up to 0.8 millimeter diameter, are corroded and carry coronas of fine-grained orthopyroxene crystals. The few orthopyroxene megaphenocrysts occur as euhedral prisms up to 0.7 millimeter in length. The refractive index, $nZ = 1.695$ on cleavage fragments, and optic angle determination, (negative) $2V = 80°$, of one orthopyroxene crystal imply a composition of $En_{75}$. The groundmass is composed of abundant orthopyroxene prisms up to 0.15 millimeter in length, with clinopyroxene as flanking plates on a few of them, and abundant tiny crystals and chains of opaque oxide (both adhering to and included in the orthopyroxene) and dustlike particles in the dark-brown, nearly opaque glass basis which composes about 25 percent of the volume of the rock. The centers of groundmass plagioclase crystals show extinction angles $X' \wedge 010_{max}$ ranging from 34° to 40° ($An_{58}$ to $An_{70}$), with rims ranging down to compositions as low as $An_{48}$. Optic angles of six groundmass orthopyroxene crystals range from (negative) $2V=65°$ to 68° ($En_{61}$ to $En_{65}$). These exceptionally low values of En content are confirmed by the higher birefringence and stronger pleochroism observed in thin section.

A specimen of lava erupted in September 1949 (specimen FP–20–49, analysis 18, table 2) is moderately vesicular and porphyritic hyalo-ophitic in texture. It contains 0.6 percent by volume (vesicle-free) of olivine megaphenocrysts and 1.3 percent by volume of orthopyroxene megaphenocrysts. The olivine crystals show less embayment than those of previously described specimens but carry distinct rims of small orthopyroxene crystals. The orthopyroxene megaphenocrysts are euhedral prisms ranging up to 0.8 millimeter in length and show optic angles (negative) $2V$ ranging from 76° to 86° (implying $En_{72}$ to $En_{80}$). The groundmass consists of abundant plagioclase laths up to 0.15 millimeter in length (with rare tablets up to 0.4 millimeter in length), abundant prisms of orthopyroxene up to 0.1 millimeter in length, as well as some orthopyroxene microlites in an abundant clear brown glass basis which composes about 25 percent of the volume of the rock. No clinopyroxene or opaque oxide was observed. Optic angles of two groundmass orthopyroxene crystals show (negative) $2V=75°$ ($En_{71}$).

A specimen of lava erupted in September 1950 (specimen FP–20–50, analysis 19, table 2) is very vesicular and has a hyaloophitic texture. It contains no olivine megaphenocrysts but 1.2 percent by volume of orthopyroxene megaphenocrysts, which occur as euhedral prisms up to 0.8 millimeter in length, some in clusters of several crystals (pl. 10, fig. 4). Refractive index on cleavage fragments of megaphenocrysts was found to be $nZ=1.704—1.706$ implying compositions of $En_{68}$ to $En_{69}$. Optic angles of five megaphenocrysts were found to range from (negative) $2V=75°$ to 79° (implying $En_{71}$ to $En_{74}$). The groundmass consists of abundant laths and tablets of plagioclase up to 0.2 millimeter in length and abundant prisms of orthopyroxene up to 0.1 millimeter in length (a few with flanking plates of clinopyroxene), in an abundant clear brown glass basis composing about 25 percent of the volume of the rock. Refractive indices of fragments of the groundmass plagioclase showed $nX'=1.557$ approximately, implying compositions near $An_{55}$. Optic angle of one orthopyroxene crystal of the groundmass showed (negative) $2V=69°$ ($En_{66}$). Refractive index of the glass showed a range of $n=1.538$ to 1.543.

Specimen FP–16–52 (analysis 22, table 2, pl. 10, fig. 5), from the last lava erupted, was collected at the vent a few days after lava activity had ceased on Feb. 25, 1952. It is quite vesicular and in thin section shows 0.3 percent by volume of olivine megaphenocrysts, which range up to 0.6 millimeter diameter and carry thin reaction rims of orthopyroxene. Also present is 0.7 percent of euhedral orthopyroxene megaphenocrysts up to 0.5 millimeter in length and 0.1 percent of plagioclase megaphenocrysts up to 0.35 millimeter in length. One orthopyroxene megaphenocryst in the thin section had (negative) $2V=79°$ and grains in immersion liquids showed $nZ=1.692$, implying a composition about $\mathrm{En}_{75}$.

Groundmass consists of abundant plagioclase microphenocrysts, generally better formed than in most earlier lavas; many orthopyroxene microphenocrysts; abundant microlites of orthopyroxene and clinopyroxene; dust-size magnetite in some areas; and a brown-glass mesostasis (10–20 percent by volume), which in some areas is made nearly opaque by dusty inclusions and in other areas is translucent. The central portions of the plagioclase microphenocrysts show $X'\wedge 010_{max}=33°–38°$ ($\mathrm{An}_{56-66}$) and $X'\wedge 010 \perp a=32°–36°$ ($\mathrm{An}_{60-70}$). Refractive index on cleavage, $nX'=1.562$, implying compositions about $\mathrm{An}_{65}$. Zoning is normal progressive and only slightly marked, except at the extreme edges of the crystals where $X'\wedge 010 \perp a$ ranges down to as low as 30° ($\mathrm{An}_{56}$) in some crystals. Orthopyroxene microphenocrysts have (negative) $2V=75°–78°$, implying compositions of $\mathrm{En}_{71-73}$. Quite a few are intergrown or coupled with plagioclase microphenocrysts, and still others show narrow flanking plates of clinopyroxene.

## INDIVIDUAL CONSTITUENTS

The major constituents of the successive lava ejecta of Parícutin volcano include plagioclase, olivine, orthopyroxene, clinopyroxene, opaque oxide, and glass. In this section the occurrence of each mineral as megaphenocrysts, microphenocrysts, and microlites will be described, with the discussion of paragenetic relations being left to a later section. Figure 98 shows the volume percentages of megaphenocrysts in those specimens on which modal analyses have been made (table 1). Figure 99 shows relative abundance of microphenocrysts and microlites, estimated from all thin sections available, with no distinction being made between lavas and bombs.

### PLAGIOCLASE

Megaphenocrysts are rare in all Parícutin ejecta except in those of 1943 and early 1944. In one thin section of March 1943 ejecta (collected by the Instituto de Geología de México), plagioclase megaphenocrysts up to 1 millimeter in length are common, as they

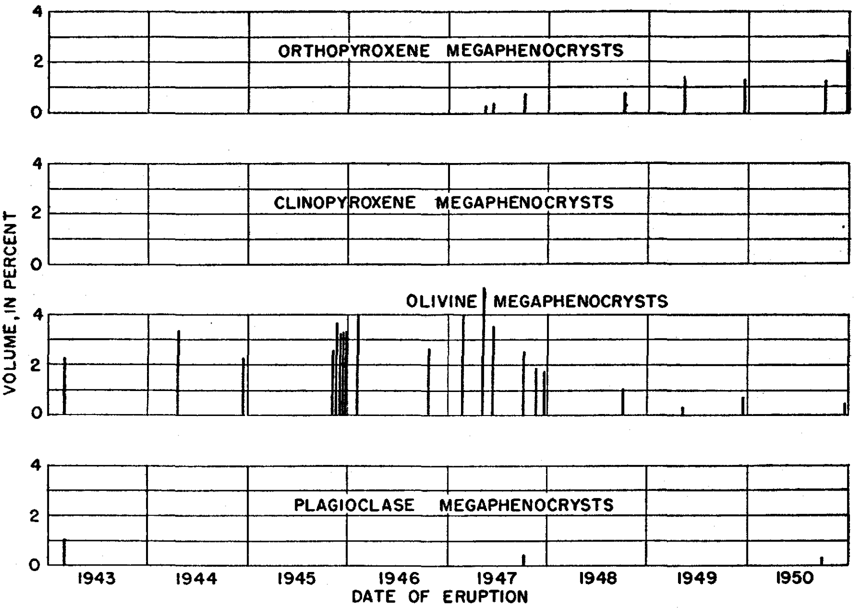


FIGURE 98.—Volume percentages of megaphenocrysts in some Parícutin ejecta, plotted according to date of eruption.

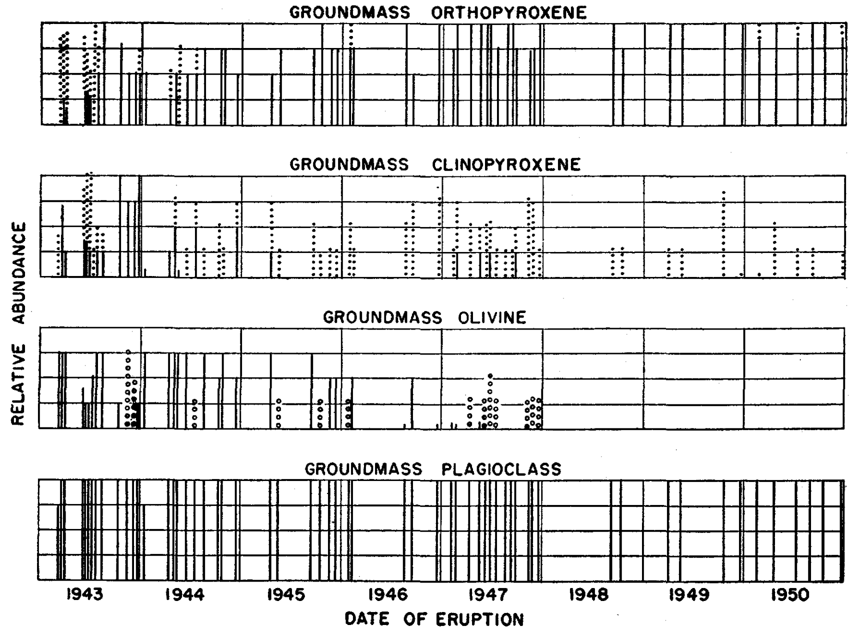


FIGURE 99.—Relative abundances of groundmass minerals in Parícutin ejecta, plotted according to date of eruption. Microphenocrysts are shown by solid bars, reacting olivine by circle bars, and microlites by dotted bars.

appear to have been in several of the 1943 specimens examined by Schmitter (1945, table 2). Zoning is generally slight, and extinction angles in thin sections examined by the writer imply compositions of $An_{68-74}$. Thin rims of some crystals are progressively zoned to as low as $An_{53}$.

Plagioclase is present as a groundmass constituent in all the ejecta of Parícutin volcano, much in contrast to its limited occurrence as megaphenocrysts. Groundmass plagioclase occurs as lath- and tablet-shaped microphenocrysts, generally not more than 0.25 millimeter long, and microlites (lengths less than 0.03 millimeter) are not generally developed. The plagioclase microphenocrysts typically show weak, progressive normal zoning in their central portions and strong, progressive normal zoning in their narrow rims. The Rittmann zone method was used to measure the extinction angles of 10 crystals in each of 7 specimens listed in table 4. The results in most specimens indicate a range of about 10 percent in apparent anorthite content from crystal to crystal. In order of dates of eruption, the average compositions for each specimen are 74, 68, 62, 63, 65, 65, 65, and 63 percent anorthite. It is thus apparent that the change in average anorthite content of plagioclase microphenocrysts from 1944-52 is not great and that the trends have not been entirely consistent. It is, of course, possible that more extensive determinations might reveal a more consistent trend. The anorthite contents of the thin rims of the plagioclase microphenocrysts range down to as low as $An_{46}$ (specimen W-47-9).

**TABLE 4.**—*Summary of anorthite contents of central portions of plagioclase microphenocrysts*

[Ten crystals determined in each specimen on universal stage]

| Analysis | Specimen | Date of eruption | Extinction angle | | Molecular percent anorthite (after Winchell 1951) [1] | |
|---|---|---|---|---|---|---|
| | | | $X'\wedge 010_{max}$ | $X'\wedge 010\perp a$ | Range | Average |
| 1 | ------ | Feb. 1943 | ------ | 36°–40° | 70–78 | 74 |
| 4 | 11-16-2 | Apr. (?) 1944 | ------ | 34°–37° | 65–73 | 68 |
| ------ | W-47-24 | Oct. 1944 | 34°–38° | ------ | 58–66 | 62 |
| 12 | W-47-9 | May 1947 | 35°–38° | ------ | 60–66 | 63 |
| 15 | W-47-30 | Sept. 1947 | 35°–40° | ------ | 60–70 | 65 |
| 16 | W-48-5 | Sept 1948 | 34°–40° | 34° | 58–70 | 65 |
| 22 | FP-16-52 | Feb. 1952 | 33°–38° | 32°–36° | 56–70 | 63 |

[1] The "high-temperature" curves of Tröger (1952, p. 113) imply anorthite contents from 6 to 11 percent lower than the values listed.

## OLIVINE

Megaphenocrysts of olivine are consistently present in all thin sections of specimens erupted before 1948. In specimens on which modal analyses have been made, olivine megaphenocrysts are present in amounts up to 4.5 percent by volume (see fig. 98), and in a few other specimens are estimated to amount to as much as 6 or 7 percent by volume. In the successive ejecta of the second half of 1947, a sudden and remarkably uniform decrease in amounts of olivine megaphenocrysts took place, and this finds its expression also in the sharp decrease in MgO-content of the analyzed specimens (fig. 100). Subsequent ejecta are characterized by a paucity of olivine megaphenocrysts. Little reaction or corrosion is shown by the olivine megaphenocrysts of 1943 and 1944 ejecta; but in later ejecta, reaction rims of fine-grained orthopyroxene become more evident.

TABLE 5.—*Refractive indices and inferred compositions of olivine megaphenocrysts in lavas of Parícutin volcano*

[~ indicates approximately]

| Specimen number | Date of Eruption | nZ | nY | nX | Composition |
|---|---|---|---|---|---|
| 51-W-18 | Mar. 1943...... | 1. 713 | 1. 692 | 1. 667 | $Fo_{80-84}$ |
| 51-W-20 | May 1943...... | 1. 711 | 1. 693 | 1. 676 | $Fo_{79-81}$ |
| W-47-9 | May 1947...... | ~1. 712 | 1. 695 | 1. 675 | $Fo_{79-80}$ |
| FP-20-49 | Dec. 1949...... | ~1. 720 | ----- | 1. 676 | $Fo_{76-81}$ |

Refractive indices and inferred chemical compositions of olivine megaphenocrysts of several lavas of Parícutin volcano are given in table 5. The range of composition is from $Fo_{76}$ to $Fo_{84}$ with the major bulk of megaphenocryst material judged to be of compositions between $Fo_{80}$ and $Fo_{78}$. A decrease of $2V_{\text{over } X}$ of 2° to 3° from center to rim of some crystals implies 4 to 6 percent less Fo in the rims than in the center. The olivine megaphenocrysts characteristically carry tiny euhedral crystals of opaque oxide up to 0.01 millimeter diameter, as scattered individuals or in clusters or strings. Those examined by the writer have been found to be opaque even in the most intense light and are presumed to be magnetite or titanomagnetite; it is noted, however, that Schmitter (1945, table 2) identified spinel inclusions in olivine phenocrysts of several specimens erupted in 1943. Because of the presence of these inclusions, the bulk compositions of the olivine megaphenocrysts no doubt is slightly higher in iron than indicated by optical properties.

The olivine of the groundmass occurs as microphenocrysts and grains in widely varying amounts in the ejecta of 1943–46; in a few specimens the texture is seriate, and the distinction between megaphenocrysts and microphenocrysts (and grains) of olivine is made by using the arbitrary 0.3 millimeter limit. The optic angle of one groundmass crystal of olivine in a lava of 1944 (Krauskopf specimen 11–23–2) is (negative) $2V=88°$, corresponding to a theoretical composition of $Fo_{74}$. Excellently formed microphenocrysts of olivine are found in some of the pumice and lapilli ejected from the main vent during 1943 (see pl. 10, fig. 2), and these show little or no reaction. Reaction rims of orthopyroxene around grains of groundmass olivine appear in some ejecta of 1943–45 and become increasingly wider in ejecta of 1946 and 1947. No groundmass olivine was found in post-1947 ejecta.

### CLINOPYROXENE

Clinopyroxene does not occur as megaphenocrysts in Parícutin specimens except in rare circumstances. In the groundmasses of several of the earlier lavas and bombs of Parícutin volcano, microphenocrysts of clinopyroxene, rarely as much as 0.1 millimeter long, are moderately well developed. Extinction angles *Z* to *c* ranging from 45° to 51° would indicate that these crystals are augitic rather than pigeonitic. Microphenocrysts of clinopyroxene do not occur in ejecta of 1945 and 1946 but appear again in some of the ejecta of 1947.

The most common occurrence of clinopyroxene is as microlitic prisms and needles in the glassy mesostasis of the ejecta. Clinopyroxene microlites are present in the majority of lavas erupted during 1943–47 and are spasmodically present in lavas erupted after 1947. Microlitic clinopyroxene commonly occurs also as platelike overgrowths on the flanks of orthopyroxene microphenocrysts, sometimes extending as long swallowtails and bundles beyond the ends of the orthopyroxene crystals into the glass, (see pl. 10, fig. 6). These flanking plates of clinopyroxene apparently lie against the (100) faces of the orthopyroxene, with coincidence of the *b* crystallographic axes (compare Kuno, 1950, p. 978). Opaque oxide adheres so thickly to the microlitic prisms of clinopyroxene of some specimens as to obscure their optical character, while the orthopyroxene of the same specimens have few if any adherent opaque oxide. Extinction angles *Z* to *c* ranging from 45° to 50° for the clinopyroxene microlites and flanking plates imply that they are augitic rather than pigeonitic.

### ORTHOPYROXENE

Megaphenocrysts of orthopyroxene are characteristically present in the Parícutin material erupted after 1946, but they are rarely present in earlier ejecta. In figure 98 it is seen that olivine gives way to orthopyroxene as the predominant megaphenocrysts in the later lavas and that the transition occurred mainly during 1947. Orthopyroxene megaphenocrysts occur generally as thick prisms up to 1.0 millimeter in length, rarely up to 1.4 millimeter, and as cruciform growths and clusters of several crystals. (See pl. 10, fig. 4.) They show weak but perceptible pleochroism, and optic angle measurements imply compositions from $En_{70}$ to $En_{80}$. (See table 6.) Refractive index of orthopyroxene megaphenocrysts of specimen W–48–5 (analysis 16, table 2) showed $nZ=1.695$, from which a composition of $En_{75}$ is inferred.

TABLE 6.—*Optic angles of orthopyroxene, with compositions inferred from curves of Winchell (1951, fig. 283)*

| Specimen | Date of Eruption | Megaphenocrysts |  |  |  |  | Microphenocrysts |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Number determined | Range (−) $2V$ | Molecular percent En |  |  | Number determined | Range (−) $2V$ | Molecular percent En |  |  |
|  |  |  |  | Minimum | Maximum | Average |  |  | Minimum | Maximum | Average |
| 11-16-1 | Apr. (?) 1944 |  |  |  |  |  | 2 | 68°–70° | 65 | 67 | 66 |
| W-47-9 | May 1947 |  |  |  |  |  | 3 | 72°–75° | 69 | 71 | 70 |
| W-47-30 | Nov. 1947 |  |  |  |  |  | 7 | 70°–79° | 66 | 74 | 71 |
| W-48-5 | Sept. 1948 | 1 | 80° |  |  | 75 | 6 | 65°–68° | 61 | 65 | 64 |
| W-48-9 | Oct. 1948 |  |  |  |  |  | 1 | 68° |  |  | 65 |
| FP-20-49 | Dec. 1949 | 5 | 76°–86° | 72 | 80 | 75 | 2 | 75° |  |  | 71 |
| FP-20-50 | Sept. 1950 | 5 | 75°–79° | 71 | 74 | 73 | 5 | 69°–76° | 66 | 72 | 68 |
| FP-55-50 | Dec. 1950 | 1 | 74° |  |  | 70 | 2 | 68°–69° | 65 | 66 | 65 |
| FP-16-52 | Feb. 1952 | 1 | 79° |  |  | 74 | 4 | 75°–78° | 71 | 73 | 72 |

Orthopyroxene occurs in the groundmasses of the great majority of the Parícutin lavas and bombs. In only a few of the rocks is it lacking or doubtfully present, notably those erupted during 1943. In most of the 1943 and 1944 lavas, it is found as microlites and microphenocrysts of varying length and slimness from specimen to specimen, mostly too small for measurement of optic angles. In the later lavas it is found as larger prisms, and through successively erupted specimens the maximum lengths of the orthopyroxene prisms increases gradually until in 1947 the maximum exceeds 0.3 millimeter, the arbitrary boundary size between microphenocryst and megaphenocryst set here. Optic angles of orthopyroxene microphenocrysts, given in table 6, show a range of (negative) $2V$ from 65° to 79°, from which a compositional range of $En_{61}$ to $En_{74}$ is inferred. There is only a slight, if any, trend towards lower En content in later ejecta, but it is apparent that the compositions of the microphenocrysts are consistently lower in En content than the megaphenocrysts in the corresponding specimens. In many specimens clinopyroxene overgrowths are common (pl. 10, fig. 6) as thin plates on the (100) faces of the orthopyroxene, as described above in connection with clinopyroxene.

### OPAQUE AND ACCESSORY MINERALS

No attempt was made to distinguish between the various possible opaque minerals encountered in the examination of the thin sections except to establish that yellow metallic sulfides were not present in observable amounts or grain sizes. On the basis of the octahedral-like form of some of the better formed crystals and on the bulk chemical analyses, it is concluded that most of these opaque crystals are magnetite or titaniferous magnetite. The opaque material occurs in several situations: as isolated, tiny, well-formed crystals up to 0.02 millimeter in diameter and groups included in olivine and orthopyroxene phenocrysts, as tiny crystals, cluster and skeletal groups in the groundmass, and as minute dustlike particles distributed through the glassy mesostasis of many of the rocks. In many specimens the opaque crystals are seen to adhere individually or in clusters to the microlites and larger crystals of ferromagnesian minerals, particularly to the clinopyroxene microlites. Accessory minerals were not searched for systematically other than to determine that the great preponderance of the tiny, low-birefringent microphenocrysts were orthopyroxene rather than apatite, which, from the bulk chemical compositions, can be expected to be present in small amount.

### GLASS

Glass is consistently present in the suite of rocks from Parícutin. It varies in amount from a diffuse mesostasis to an appreciable portion of the groundmass. All gradations in transparency are found, from clear light-brown glass carrying scattered well-developed microphenocrysts of ferromagnesian minerals and plagioclase to nearly opaque material which is seen under high magnification to be croweded with ferromagnesian microlites, opaque dustlike particles and minute vesicles. There seems to be a tendency for more common occurrence of clear glass in the very early ejecta (1943–44) and in the late ejecta (1949–52). Representative refractive indices of the clearer glasses are shown in table 7, and indicate a trend towards more salic compositions of the glass in the later ejecta.

TABLE 7.—*Refractive indices of glassy mesostases of some Parícutin lava specimens*

| Specimen | Date erupted | Description | Refractive index of glass |
|---|---|---|---|
| 51–W–23 | 1943 | Bomb | 1.565–1.568 |
| W–48–9 | Oct. 1948 | Lava | 1.542–1.547 |
| FP–20–50 | Sept. 1950 | Lava | 1.538–1.543 |

### XENOLITHS

Some 20 xenoliths, mostly from Parícutin bombs, have been examined in thin section. In hand specimen all of these are light colored, contrasting with the black and dark brown of the normal Parícutin material. The majority consist of highly vesicular glass through which are distributed grains of quartz, feldspar, and ferromagnesian minerals in various stages of destruction. Both plutonic and extrusive rock types appear to be represented in the specimens studied and include granite, granodiorite, quartz monzonite, and as near as could be determined, relics of dacitic and rhyolitic porphyries.

One xenolith (specimen 51–W–1, analysis X–1, table 3) erupted as the nucleus of a bomb in 1943 is only slightly altered and shows a coarse granitic texture. It contains abundant anhedral grains of fractured and cloudy orthoclase up to 7 millimeters in diameter, many roughly euhedral crystals up to 3 millimeters in diameter of fractured and cloudly plagioclase of composition about $An_6$ ($nX'$ on cleavage ranges from 1.527 to 1.529), about 20 percent by volume of anhedral quartz grains up to 0.4 millimeter in diameter, and about 15 percent by volume of masses of opaque material, some of which, by their outline and internal structure, must be relics of ferromagnesian minerals. Titanite, zircon, and apatite are present as accessories. The start of thermal breakdown of the rock is revealed by the thin veinlets of vesicular glass in the feldspars and along crystal contacts (see pl. 11, fig. 1), by the opaque pseudomorphs of the ferromagnesian minerals, and by incipient fracturing and development of streaks of tiny bubbles along fractures in the quartz. Otherwise the rock is a normal quartz monzonite, similar to the quartz monzonite-granodiorite suite outcropping along the edge of the plateau not far to the south of the Parícutin region.

A similar xenolith, (specimen 51–W–9, analysis X–3, table 3) erupted during 1944 or 1945, contains about equal amounts of anhedral orthoclase grains up to 2 millimeters in diameter and subhedral crystals of plagioclase up to 4 millimeters in length. About 20 percent by volume of anhedral quartz grains and 15 percent of irregular to rectangular masses of opaque oxide, no doubt relict ferromagnesian minerals, make up the remainder of the rock. Much of the plagioclase is both polysynthetically twinned and oscillatorily zoned. Predominant compositions lie between $An_{25}$ and $An_{28}$ ($nX'$ on cleavage$=$1.541–1.543) while some range down to $An_{16}$ ($nX'=1.535$). Both orthoclase and plagioclase are much fractured and carry many minute inclusions (both bubbles and solid material?). The feldspars are veined by vesicular glass as in specimen 51–W–1, but in addition narrow border zones of some feldspar grains are "fritted." The term "fritted" is used here to describe the minutely wrinkled or reticulate texture frequently encountered in feldspars that have been heated to high temperatures (Larsen and Switzer, 1939, p. 564 and pl. 2; Wilcox, 1944, p. 1058, and pl. 5). The intense thermal expansion apparently causes separation along the two cleavages of the feldspar and subsequent internal corrosion in these fractures to give, upon quenching, a regularly spaced reticulite of glass in which the now isolated blocks of feldspar retain their original orientation fairly closely. The process of solution under dry conditions would consist chiefly of simple melting; in the presence of mineralizers such as water, the breakdown to liquid would be facilitated and could take place at lower temperatures. The mechanism in orthoclase above 1170° C should also include incongruent melting to form leucite as well as liquid (Morey and Bowen, 1922), in which case, however, the leucite could not be distinguished easily from the glass under the microscope.

Quartz grains in this specimen show marked undulatory extinction and incipient fracturing, with development of streaks of minute bubbles. The masses of opaque oxide, some rectangular in outline, show streaks and thin lenses of translucent birefrigent material parallel to their long dimension that, under intense illumination, are reminiscent of cleavage in amphiboles. The translucent material is brown in reflected light. This rock is classed as a quartz monzonite near granodiorite.

Another xenolith (specimen 51-W-4, erupted in 1943) illustrates an advance stage of disintegration of this type of granodiorite or quartz monzonitic rock. Frothy glass is predominant in this xenolith (see pl. 11, fig. 3), and its refractive index ranges from 1.484 to 1.490. Scattered through the vesicular glass are irregularly embayed quartz grains up to 0.7 millimeter in diameter showing strong undulatory and patchy extinction with development of streaks of tiny bubbles along some of the fractures. Scattered plagioclase relics of irregular shape show wide borders of fritting. The unfritted central portion of one grain showed an extinction angle of $X' \wedge 010_{max} = 20°$, which implies a composition of about $An_{37}$. Most of the scattered relics of orthoclase and microcline up to 1.3 millimeter in diameter are fritted throughout. The optic angles of four fritted grains of orthoclase, measured on the universal stage, are (negative) $2V = 59°$, 62° 62°, and 66°. Ferromagnesian relics are virtually absent in this specimen although they may be represented by the patches of light-brown glass that occur throughout.

Specimen 51-W-8 (analysis X-4, table 3), erupted during 1944 or 1945, is composed predominantly of pumiceous glass through which are scattered fragments and relics of quartz and feldspar with some macroscopically visible streaks of darker material. Original fractures in the rock are emphasized in the relic by their dark borders and high degree of vesiculation. The vesicular glass is clear and colorless with refractive index ranging from 1.489 to 1.493. The many irregular- and cusp-shaped fragments of feldspar range in size up to 0.9 millimeter in diameter and show marginal fritting and numerous veinlets of vesicular glass, very few show lamellar twinning. Scattered cusp-shaped grains of quartz range up to 0.7 millimeter in diameter and commonly show undulatory extinction and incipient fracturing. Opaque oxide and relics of ferromagnesian minerals are rare, and the rock may originally have been granite or rhyolite tuff.

A xenolith representative of extrusive or hypabyssal rock, perhaps originally a dacite or quartz latite porphyry, is illustrated by specimen 51-W-6, erupted in 1943 (see pl. 11, fig. 4). In hand specimen it is finely vesicular, carrying abundant phenocrysts, buff to white feldspar, and white quartz. In thin section the phenocrysts are seen to consist of many stubby plagioclase crystals up to 4 millimeters in diameter, some stubby orthoclase crystals up to about 4 millimeters, some subhedral quartz crystals up to 0.3 millimeter, and a few masses of opaque oxide up to 0.8 millimeter irregular to rectangular in outline (relics of ferromagnesian minerals?). The groundmass is predominantly of vesicular glass, refractive index ranging from 1.485 to 1.492, through which are scattered quartz grains up to 0.05 millimeter in diameter with irregularly scalloped outline, clots of fine-grained material of low index and relief (feldspar relics?), and clots and streaks of dark material that contain a few microlitic prisms up to 0.03 millimeter in length of moderate birefringence and relief and small globular masses of high birefringence and relief. The plagioclase phenocrysts are not particularly fritted but are clouded by many tiny bubbles and (?) glass inclusions. Although inclusions in the plagioclase are too abundant for confident determination of refractive indices, the well-developed polysynthetic twinning permits determination of extinction angles on some crystals. Two crystals with albite-carlsbad twins gave extinction angles that imply compositions of $An_{40}$ and $An_{30}$. These and others show some zoning. The orthoclase phenocrysts are similar to the plagioclase in content of tiny vesicles and inclusions. The quartz phenocrysts have rounded corners, few inclusions, and show moderate cracking and incipient shattering. One direction of parting in the quartz appears well developed. The rectangular masses of opaque oxide show streaks of translucent material parallel to the long dimensions similar to those in the quartz monzonite of specimen 51–W–9. Some of these masses are surrounded by zones of brown glass with index greater than balsam.

Specimen 51–W–7, a xenolith erupted in 1944 or 1945, is similar in most respects to specimen 51–W–6 and is regarded as having been originally a dacite or quartz latite porphyry. Refractive index of the vesicular glass ranges from 1.490 to 1.494. The feldspar phenocrysts are more rounded and more clouded by tiny vesicles and inclusions than those of specimen 51–W–6. Precise refractive index determinations were not possible, but the extinction angle for one crystal of plagioclase imply a composition of about $An_{45}$. Measured optic angle of one orthoclase crystal gave (negative) $2V=80°$. This specimen contains a few clear fragments that are presumed to be olivine; one crystal has a measured optic angle (negative) $2V=83°$, implying a composition of $Fo_{70}$. These fragments were found in only one portion of the slide, not clearly associated with any other dark materials yet definitely inclosed by the glassy groundmass so that they cannot be regarded as having been introduced during grinding of the thin section. It is possible that the thin section here cuts across a portion of the transition zone between xenolith and lava and that the olivine is an advance crystalline representative of the surrounding lava (compare description of "Inclusión de Marzo" on page 312).

A further variation of the xenoliths supposed to be dacite or quartz latite porphyry is shown in specimen 51–W–5, (analysis X–2, table 3) erupted during 1943. The phenocrysts consist of much damaged feldspar and ferromagnesian relics with some euhedral quartz crystals in a groundmass of highly vesicular glass that carries abundant small quartz grains of scalloped outline and relics of feldspar. The unique feature of this specimen is the profuse development of vesicles in the feldspar phenocryst relics. These vesicles, mostly less than 0.4 millimeter in diameter, are distributed uniformly through the crystals, which in this inflated condition range up to 5 millimeters in diameter. The central portions of a few of the crystals are less vesiculated and retain some of the optical characters of feldspars. The vesiculated portions are composed of glass in which occur innumerable tiny elongate particles up to 0.005 millimeter in length having moderate birefringence and parallel extinction. These impart brown to the crystal when viewed at low magnifications. It seems reasonable to suppose that the rock was already greatly altered, either hydrothermally or by weathering, before it was taken into the Parícutin magma and that the uncommon inflation of the feldspar phenocrysts took place when the heat of the magma caused the evolution of the water from hydrous alteration products of the original feldspar.

A unique xenolith of gray obsidian (specimen 51–W–2), which was erupted as a bomb and was collected by F. H. Pough in July 1945, does not fit in either of the above-described classes of xenoliths. Two types of material compose this xenolith. Type 1, which predominates, is fairly dense, gray obsidian in hand specimen; and as seen in thin section, it consists of slightly to moderately vesicular glass crowded with microlites and also containing some fragments of plagioclase and a few fragments of orthopyroxene. Type 2 occurs as dark streaks and whorls in the hand specimen; and as seen in thin section, it consists of abundant plagioclase crystals and fragments and minor amounts of orthopyroxene crystals in a mesostasis of clear glass (see pl. 11, fig. 6). The glass of type 1 contains so many microlites that its index could only be determined to lie between 1.491 and 1.497. Its microlites show very low interference colors, have indices much higher than the enclosing glass and range in size up to 0.002 millimeter. The index of the glass mesostasis of type 2 was found to lie in the same range of 1.491 to 1.497. The plagioclase occurs as sharply angular fragments up to 1 millimeter in diameter, while many of the smaller plagioclase crystals appear to be complete crystals strictly euhedral in outline. They are clear, moderately zoned and twinned, and show no fritting. Refractive indices, $nX'$ on cleavage, range from 1.558 to 1.562, implying compositions of $An_{60}$ to $An_{64}$. The central portion of one albite-carlsbad twin showed extinction angles of 22° versus 32° implying a composition of $An_{64}$. The outer portion of the same crystal showed extinction angles of 20° versus 27°, implying $An_{56}$. Another crystal showed $X' \wedge 010_{max} = 34°$ implying a composition of $An_{63}$. Orthopyroxene occurs as scattered crystals and fragments, some showing corrosion and some carrying adherent opaque oxide particles. Their pleochroism is slightly more marked than that of the orthopyroxene of the normal Parícutin lava, and their refractive indices ($nZ$ on cleavage about 1.702) imply a composition of about $En_{70}$. Rare relics of other ferromagnesian minerals (xenocrysts?), now mostly opaque oxide, are seen. The moderately calcic nature of the plagioclase ($An_{60-64}$) and high magnesian content of the orthopyroxene ($En_{77}$) seems incongruous when compared to the apparently salic nature of the abundant enclosing glass (n=1.491–1.497). Such relations are found, however, in some transition zones between xenoliths and lava (see description of transition zone of specimen FP–11–49, below), and it may be that this specimen is part of a broad transition zone or of a once completely melted salic xenolith.

It is interesting to note that in the pre-Parícutin lavas of the region, the xenolithic material which is occasionally encountered is much the same as has just been described for the ejecta of Parícutin volcano. Thus, specimen W–48–7; a xenolith collected at Cuezeño from a lava flow of nearby Tzintzungo volcano (see Williams, 1951, pl. 8), resembles very closely the Parícutin xenolith specimen 51–W–9. A block of light-colored pumiceous material (specimen W–48–4) was found by the writer among blocks of normal lava in a wall in Angahuan village; and from what could be learned from the residents, all the blocks had been gathered in the immediate vicinity years before when the wall was built. No doubt the pumiceous block was a xenolith of the prehistoric eruption of Tzintzungo volcano, lava of which covers the area. This specimen represents a more advanced stage of disintegration than W–48–7 and is comparable in most respects to the Parícutin xenolith, 51–W–4, described above.

A granodiorite (specimen FP–20–52, pl. 11, fig. 2), from what is probably the nearest outcrop area of salic plutonic rock 30 kilometers SE. of Parícutin volcano, is of interest for comparison with the Parícutin xenoliths. Its texture is xenomorphic—granular with plagioclase grains up to 1.5 millimeter in diameter composing about 35 percent by volume. Progressive normal zoning is common, and some crystals range from as high as $An_{70}$ at their centers to as low as

$An_{23}$ at their edges. The major portion appears to be between $An_{30}$ and $An_{40}$. Orthoclase grains up to 1 millimeter in diameter compose about 25 percent by volume and quartz grains up to 0.5 millimeter about 20 percent, both being generally interstitial to the plagioclase. Clinopyroxene grains up to 0.7 millimeter in diameter are the most common of the ferromagnesian constituents and compose about 10 percent by volume. Orthopyroxene, sometimes intergrown with clinopyroxene and always much altered, occurs sporadically. Biotite, amphibole (?) and opaque oxide crystals, and clots compose the remainder of the rock with very minor amounts of apatite and zircon as accessories. Except for its somewhat more mafic character, the rock is similar to many of the coarse-grained Parícutin xenoliths.

## TRANSITION ZONES BETWEEN LAVAS AND XENOLITHS

Of the specimens in which both lava and xenolith are present, the contacts between dark lava and light xenolith are sharply defined to the unaided eye, and obvious effects of mixing and strewing of one material in the other are absent. In thin section the gradation in color from the dark-brown glass mesostasis of the lava to the colorless glass of the xenolith occurs across a zone usually less than a millimeter wide at most contacts. The gradation in mineral content, however, may extend several more millimeters into the xenolith and is revealed by the growth of isolated microphenocrysts of plagioclase and ferromagnesian minerals in the otherwise normal appearing, colorless glass of the xenolith. In the thin section of a few of the specimens, stringers of brown glass carrying plagioclase and ferromagnesian crystals are seen to penetrate for distances of a centimeter or more into the xenolith.

A transition zone is well developed in a thin section of an "Inclusión de Marzo 1943" loaned by the Instituto de Geología de México. This xenolith is apparently of the quartz monzonite type, described above, with irregularly shaped grains of quartz and fritted orthoclase and plagioclase distributed through a matrix of colorless vesicular glass of index much lower than that of balsam. The surrounding lava contains scattered euhedral phenocrysts of olivine up to 1.5 millimeter in diameter and a few lath-shaped phenocrysts of plagioclase up to 0.6 millimeter in length in a groundmass that consists of abundant plagioclase laths, many microphenocrysts and grains of olivine, abundant prisms of orthopyroxene, and a glassy mesostasis which contains variable amounts of microlites and dusty particles. The width of gradation from brown to colorless glass in the transition zone between lava and xenolith is variable but rarely exceeds 0.8 millimeter. The glass of this zone not only carries fragments of xenolith crystals (quartz and feldspar) but also slender euhedral laths of plagioclase up to 0.03 millimeter in length and stubby euhedral crystals of olivine up to 0.01 millimeter in diameter. No corrosion or reaction coronas are seen on the olivine crystals, even where they occur sparsely out in the colorless glass.

An inclusion in Parícutin lava collected from the vent cascade October 17, 1949, (specimen FP–11–49) shows an exceptionally broad transition zone several millimeters wide. The xenolith proper is composed of many irregular grains of quartz and orthoclase up to 1.5 millimeters in diameter immersed in clear, colorless glass of refractive index lying between 1.486 and 1.491. Large plagioclase grains are sparsely present, one crystal showing extinction angles that indicate a composition of about $An_{30}$. Ferromagnesian minerals appear to be absent. The enclosing lava is similar to the normal lava that was erupted at that time (see description of specimen FP–20–49, above) with a glass mesostasis of refractive index about 1.524–1.528. The transition zone is variable in the proportion of crystalline material to glass, and the glass becomes generally lighter in color towards the xenolith. Streaks of lava penetrate the xenolith for several millimeters, and conversely the xenolithic material penetrates the lava proper. Grains of quartz and orthoclase, the latter more fritted than in the xenolith (see pl. 11, fig., 5), as well as phenocrysts of orthopyroxene and olivine are scattered through the transition zone. From the lava proper to the xenolith proper the groundmass crystals ("microphenocyrsts") are consistently euhedral calcic plagioclase laths and orthopyroxene prisms, and they become less abundant towards the xenolith.

It is noted for the normal Parícutin lavas in general that isolated quartz grains are encountered in some hand specimens and thin sections, always of irregular shape and showing evidence of reaction. Individual alkali feldspar grains are rarely found, being almost unrecognizable in hand specimen and recognized in thin section by their fritted texture and remnants of feldspar optical characters. The greater persistence of quartz xenocrysts may be explained chiefly by their physical structure, that is, lack of cleavage or parting that would cause rapid disintegration under thermal stress.

## PETROCHEMISTRY

Twenty-two chemical analyses of lavas of Parícutin volcano, selected as satisfactory from the standpoints of both quality of analysis and of definiteness of date of eruption (within 2 months), are listed in table 2 along with four analyses of xenoliths in table 3. Participating analysts were Charles Milton, Erma Chadbourn, James Kerr, Harry H. Hyman, Edythe Engleman, and Lucile Tarrant, all except Milton working under the supervision of Lee C. Peck. Normative mineral compositions are given in table 2, and Niggli values of analyses 1, 2, 3, and 5 have been published by Williams (1950, table 3). Calculated groundmass compositions of several specimens are given in table 2. Spectrographic analyses of these lavas and xenoliths, as well as of lava specimens of Williams (1950) for the Parícutin region, have been made by K. J. Murata and will form the basis of a separate paper by him.

Chemical compositions of lava specimens have been plotted against dates of eruption in figure 100. For purposes of this and subsequent diagrams, the ferric iron of each analysis has been recalculated as ferrous oxide and combined with the ferrous oxide actually found in order to eliminate confusion owing to the erratic but generally reciprocal relations between ferrous and ferric iron. The new value of ferrous oxide and the values of the nine other major oxides ($SiO_2$, $Al_2O_3$, MgO, CaO, $Na_2O$, $K_2O$, $TiO_2$, $P_2O_5$ and MnO) were adjusted to total 100 percent and were plotted as open circles on the diagram according to dates of eruption of the specimens.

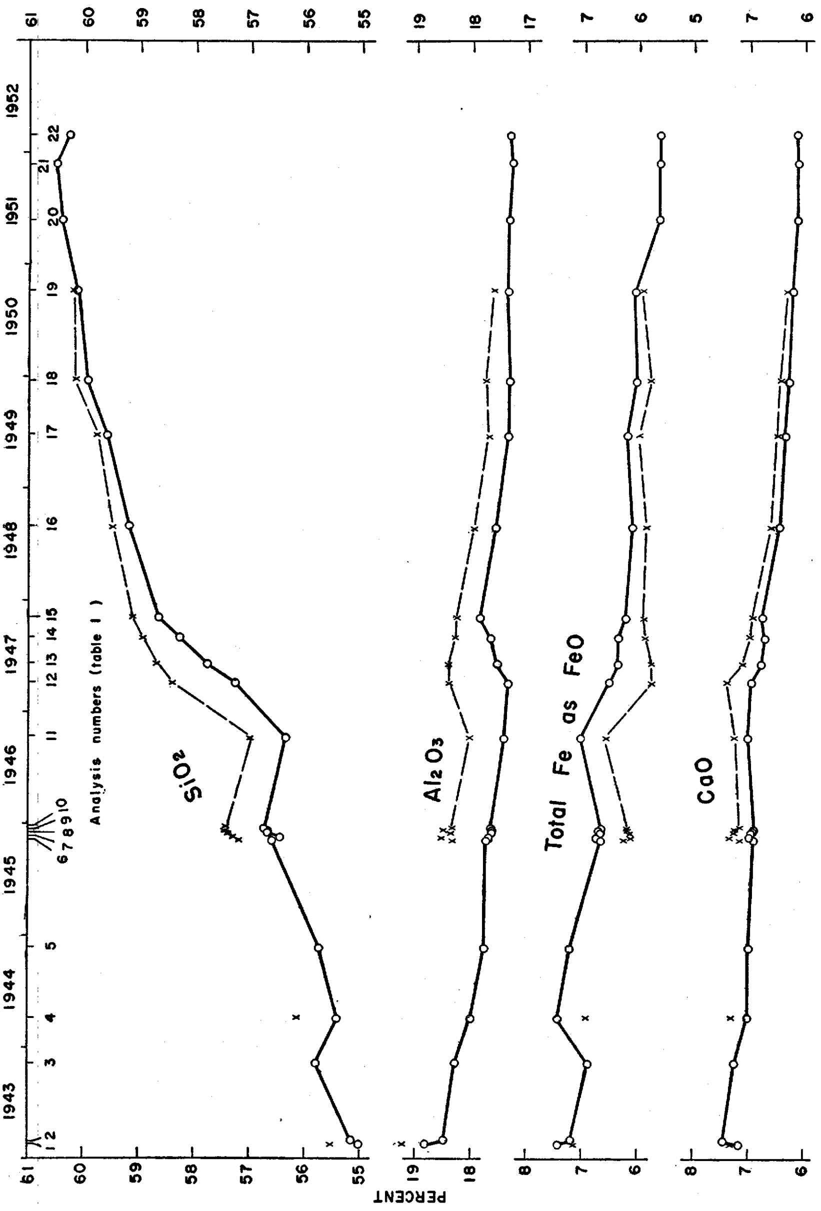
The resulting graph of figure 100 shows in a striking manner that the oxide constituent of successively erupted lavas have varied serially during the course of the eruption. Silica increased from about 55 percent in 1943 to slightly over 60 percent in 1952; potash increased consistently if only a small amount; soda remained nearly constant, while alumina, iron oxide, lime, and magnesia decreased. During 1947, an extra rapid increase in silica took place while alumina also increased slightly and magnesia decreased rapidly. The specimens of analyses 6–10 of table 2 were collected by K. B. Krauskopf from lava erupted during November and December 1945 in order to determine the variation of lava composition over a short period of eruption and, in the case of analyses 8 and 9, the variation between toe and vent of the same flow. It is seen from the analyses and from figure 100 that the variations of analyses 6–10 are remarkably small, all being within one-half of 1 percent of silica and proportionately less for the other oxide constituents. Reversals of trend are represented, however, by analyses 4 and 11, which are noticeably lower in silica and higher in iron than their immediate predecessors.

The chemical relations of the lavas of Parícutin volcano are further illustrated in the silica-variation diagram of figure 101, where the recast analyses are plotted as large circles. For comparison the analyses of lavas of other volcanoes in the vicinity (recast in the same manner from Williams, 1950, table 1) are plotted as small circles. The plots of $TiO_2$, $P_2O_5$, and MnO are not shown in this diagram, because their variations with respect to silica are very small.

The close similarity in chemical trends of the lavas of Parícutin volcano to those of the volcanoes of the surrounding region is well illustrated by the silica-variation diagram, even on the large scale of figure 101. This similarity would be even more noticeable by contrast if there were room on the same diagram to plot the analyses of the lavas of the Neo-Volcanic Zone of Mexico as a whole (Williams, 1950, fig. 93). It may be remarked that the most aberrant of Williams' specimens, No. 6, a hornblende andesite, was collected from the Mesa de Zirimóndiro at the extreme southwestern corner of William's mapped area. Its abnormally high alumina content and the presence in it of amphibole to the exclusion of other ferromagnisian minerals set it apart from the normal lavas of the Parícutin region. While the silica range of the Parícutin lavas is only about half that of the Parícutin region and the Parícutin lavas are quite consistently slightly lower in alumina and slightly higher in iron and magnesia than the lavas of comparable silica content from the surrounding volcanoes, the correspondence is otherwise remarkably close; and this correspondence may imply that similar factors have controlled the chemical trends of Parícutin and neighboring lavas.

The alkali-lime index (the silica percentage at which the sum of the alkalis equals the lime, as defined by Peacock, 1931) for the lavas of Parícutin volcano is about 62 (by extrapolation) and that of the lavas of the surrounding region is 61.5 when determined according to the plot of figure 101. The alkali-lime index of the Neo-Volcanic Zone of Mexico (exclusive of the Parícutin region?) is given as 60 by Williams (1950, p. 265). Thus, all three groups of these Mexican rocks lie close to the border between Peacock's calcic and calc-alkalic igneous series.

Calculated compositions of groundmasses, given in table 2, are plotted as crosses on figure 100. In calculating the groundmass of each specimen, its megaphenocrysts were subtracted from the bulk analyses (total Fe as FeO, and excluding $H_2O$, S, $CO_2$ and BaO) and the residue readjusted to total 100 percent. In these calculations the compositions of modal megaphenocrysts were taken as $Fo_{80}$ for olivine, $En_{75}$ for orthopyroxene, and $An_{70}$ for plagioclase. Specific gravities were taken as 3.5 for olivine, 3.4 for hypersthene, and 2.7 for plagioclase. Lacking values of the specific gravity for the individual analysed specimens, that of the bulk rocks is assumed to be 2.7. Although the actual specific gravities apparently range from about 2.8 for the earlier lavas to slightly below 2.7 for the later lavas (as seen in table 8), the assumption of a value of 2.7 for each specimen introduces no errors that approach the effects of the possible errors in determining the amount of phenocrystic material by modal analysis. It should be noted in table 8 that the percent vesicles of specimen W–46–27 determined by modal analysis in thin section would lead one to expect a much higher value of powder specific


1943
1944
1945
1946
1947
1948
1949
1950
1951
1952
1 2
3
4
5
6 7 8 9 10
11
12 13 14 15
16
17
18
19
20
21
22
Analysis numbers (table 1)
$SiO_2$
$Al_2O_3$
Total Fe as FeO
CaO
PERCENT
61
60
59
58
57
56
55
19
18
17
8
7
6
5
8
7
6

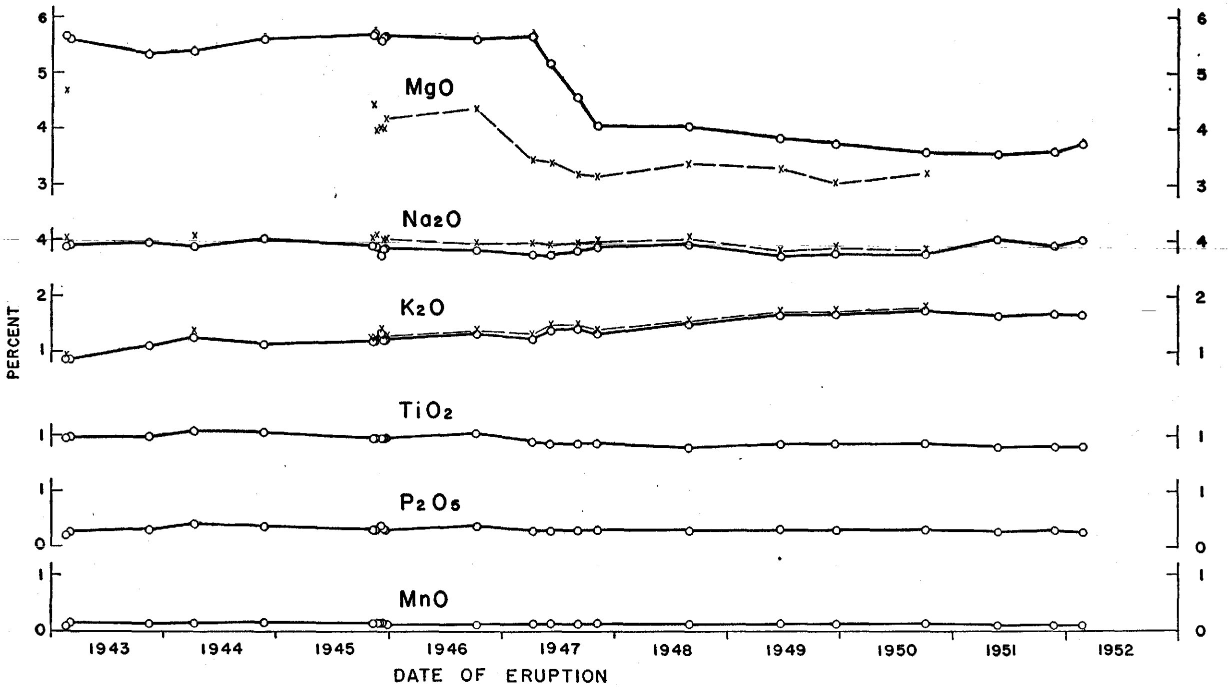


FIGURE 100.—Compositions of lavas of Parícutin volcano, plotted according to date of eruption. Bulk analyses (table 2), recast with all iron as FeO and excluding volatiles, are plotted as circles. Calculated groundmass compositions (table 2) are plotted as crosses.

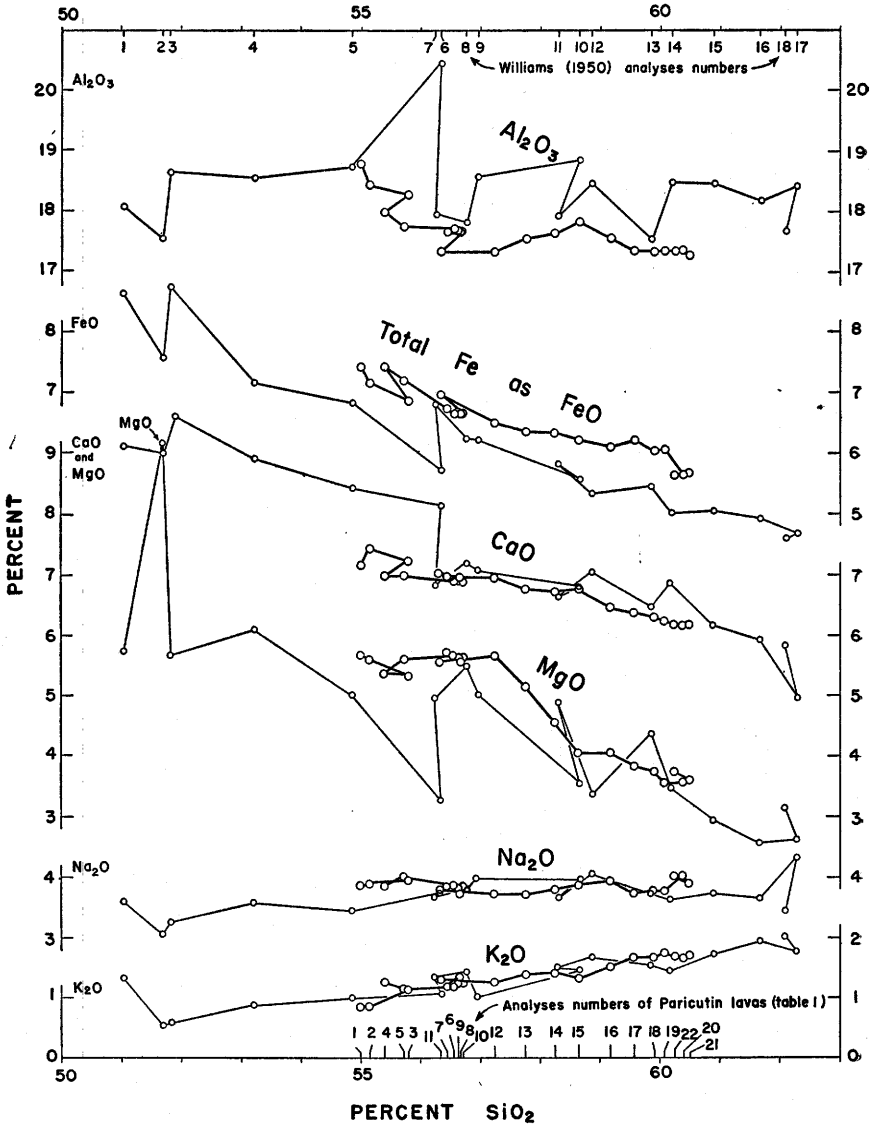


FIGURE 101.—Silica-variation diagram of lavas of Parícutin and nearby volcanoes. Large circles show lavas of Parícutin connected in order of eruption. Small circles show lavas of nearby volcanoes connected in order of analysis number (Williams, 1950, table 1). Both sets of analyses have been recast with all iron as FeO and excluding volatiles.

gravity than was actually found. It is concluded that the vesicularity of the thin section is too high, owing to loss of material during grinding; and it is probable that such error is greater, the greater the initial vesicularity of the rock.

TABLE 8.—*Specific gravities of Parícutin lavas*

| Specimen | Date erupted | Percent vesicles | Bulk specific gravity |
|---|---|---|---|
| 51–W–19 | March 1943 | Negligible | 2. 76 |
| 51–W–21 | June 1943 | Negligible | 2. 73 |
| 11–16–1 | April 1944 | 2.0 | 2. 68 |
| W–46–27 | September 1946 | 7.3 | [1] 2. 68 |
| W–47–19 | September 1947 | 5.7 | 2. 62 |
| FP–53–50 | November 1950 | Negligible | 2. 67 |

[1] Specific gravity of powder determined as 2.78 by Chemical Analysis Laboratory, U. S. Geological Survey.

## ORIGIN OF PETROGRAPHIC AND CHEMICAL TRENDS

The series of rock specimens from the protracted eruption of Parícutin volcano furnishes petrographic and chemical data that are perhaps as complete and definite in respect to time and place as have become available from any volcanic suite. In this suite, for instance, there can be no doubt that all the specimens came from the same magma chamber, that only a limited number of types of intratelluric crystals existed in the chamber and that there were no significant interruptions of the process or processes that brought about the observed diversification of rock type. Among other things, these circumstances provide a welcome opportunity to test quantitatively whether fractional crystallization alone produced the resulting rock series—a casual postulate made so often for composite suites of other geographic areas where, because of the many possible variables of time, space, and participating minerals, the postulate can neither be supported or refuted.

Limitations of the data at hand must be recognized at the outset and be kept in mind throughout. The successive lava flows from which the analyzed specimens were collected represent no more than a continuous sampling of the Parícutin magma body during the years 1943–52. It is elementary, but nevertheless important, to appreciate that the magma body was not necessarily homogeneous in 1943 and that it did not necessarily change throughout from basaltic to andesitic composition during only those years in which material was issuing from it.

The chemical and petrographic differences between successively erupted materials are strikingly apparent—the more so because of their serial nature. The problem is to deduce the mechanism by which they were produced. In the discussion which follows only two mechanisms, assimilation and fractional crystallization, are considered in respect to their individual and combined abilities to account for the observed features of the rock series. Considering only those two, the writer has been led to the conclusion that the observed trends could not have been produced by fractional crystallization alone but that they could have been produced by assimilation of granitic country rock combined with fractional crystallization of olivine and plagioclase. It is hoped that the inclusion of the basic data in some detail in the previous sections will enable other workers to evaluate the possible involvement of other mechanisms or perhaps to modify or drastically revise the relative importance of the roles permitted here to assimilation and to fractional crystallization.

## PARAGENESIS OF MINERALS

The association of the four major crystalline constituents in the Parícutin ejecta of 1943–50 are generalized in figure 102 from the detailed data of figures 98 and 99. As noted previously, the size limit between megaphenocrysts and microphenocrysts has been chosen rather arbitrarily as 0.3 millimeter and that between microphenocrysts and microlites (the latter not shown on figure 102) as 0.03 millimeter. The occurrence of olivine relics—crystals that are marginally converted to pyroxene—is indicated on the diagram by hatching. The overlapping of occurrence of relict and fresh olivine in the diagram is brought about not by the occurrence of both types in the same specimens but by alternation of the two types from specimen to specimen.

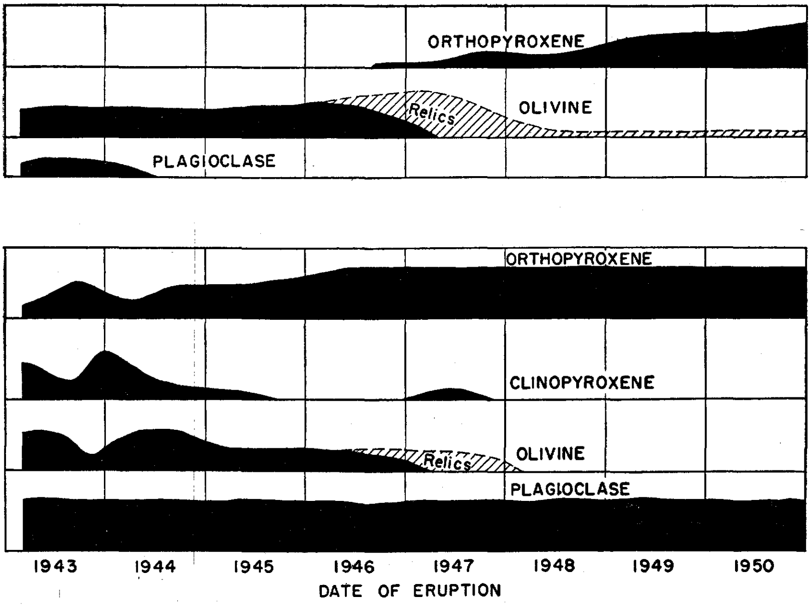


FIGURE 102.—Occurrence of megaphenocrysts (upper) and microphenocrysts (lower) in successive Parícutin ejecta of 1943 to 1950 (generalized from data of figures 98 and 99).

In most of the specimens three stages of cooling are implied by the presence of megaphenocrysts, microphenocrysts, and glass with microlites. Whereas the conventional assignment of these three to intratelluric, hypabyssal (conduit), and surficial cooling stages might be justified here, consideration will be given also the the possible cooling effect of admixture of foreign material in producing the microphenocryst generation while still at depth. A sharp demarcation between megaphenocrysts and microphenocrysts does not exist in some specimens, and here we must suppose that the change in crystallizing conditions must have been gradual. Likewise, the glassy mesostases may not have been developed in all specimens as a result of any sudden increase in the rate of cooling but simply by the inability of crystallization to keep pace with a steady cooling that had been going on for some time previously.

The degree of confidence with which one may deduce equilibrium relationships between the component minerals is, of course, not the same for the different generations. The megaphenocrysts may well represent minerals that were in equilibrium with the liquid and with each other. The microphenocrysts, however, are products of a more rapidly changing environment in which true equilibrium was never established, shown, for instance, by the progressive zoning in the plagioclase. But, although their crystallization was no doubt forced and somewhat removed from equilibrium, the degree of departure from equilibrium may have been roughly the same from specimen to specimen throughout the years of the continuous eruption, and one may be justified in making cautious comparisons through the series. The microlites, developed during the rapid congelation of the interstitial liquid, cannot be used to infer equilibrium relationships; and the conditions of this final congelation may have been so fortuitous from specimen to specimen that only the most general comparisons can be made between the microlites of the different members of the rock series.

## MEGAPHENOCRYSTS

The earliest generation of crystals represented are the megaphenocrysts: olivine and plagioclase in 1943–44 specimens, olivine alone in the 1945–47 specimens, and orthopyroxene and olivine in the 1947–52 specimens. The olivine and plagioclase megaphenocrysts of the 1943–44 specimens can no doubt be regarded as developed at depth; and lacking corrosion or reaction rims, they must have been essentially in equilibrium with each other and with the liquid until eruption at the surface. Schmitter (1945, photograph Q) notes occasional gross skeletal forms of olivine megaphenocrysts; but these, because of their symmetry, probably should be regarded as growing forms rather than dissolving or reacting forms.

It should be noted here that the general absence of plagioclase megaphenocrysts sets the later Parícutin ejecta apart from the large proportion of andesites and basaltic andesites of other localities. While volcanic rocks bearing ferromagnesian phenocrysts but no plagioclase phenocrysts are perhaps not rare, they certainly have not received much attention in literature. For lavas of the circumpacific zone, (calc-alkaline suite) Johannsen (1937, p. 174–175) cites "boninite" as an abnormal andesite that contains olivine and pyroxene phenocrysts to the exclusion of plagioclase phenocrysts; and possibly some varieties of "sanukite" mentioned by Johannsen may be included here. Larsson (1941, p. 319–321) describes four lavas of the Brazo del Viento area, northern Patagonia, in which olivine is the only phenocrystic constituent and one lava in which olivine and diopside are the only phenocrystic constituents. It is interesting that among the lavas from some of the volcanoes near Parícutin there are several examples free of plagioclase phenocrysts, notably the augite-hornblende andesite of the Mesa de Huanáracua, the olivine basaltic andesite of Cerro de Cutzato, and the olivine basalt of Cerros de Jabalí (Williams, 1950, p. 241, 248, and 253, respectively). In addition, plagioclase phenocrysts are remarkably scarce in the porphyritic lavas on the northwest flanks of Cerros de Tancítaro (Williams, 1950, p. 255). Olivine phenocrysts, but no plagioclase phenocrysts, are noted in a specimen of basalt from Jorullo volcano by Schmitter (1945, table 2, specimen 10).

The reasons for the absence of plagioclase megaphenocrysts from all but the earliest ejecta of Parícutin volcano is not at once clear. Perhaps only olivine was forming at depth, or perhaps olivine was crystallizing at a few centers to give large crystals while plagioclase was crystallizing at many centers to give small crystals. It hardly seems likely that much previously formed plagioclase could have been removed by gravity, for olivine, which would have had a much greater gravitational advantage, was not completely removed.

The loss of stability of the olivine crystals in the magma of the specimens erupted after 1944 is indicated by the appearance of reaction rims of fine-grained orthopyroxene on the olivine megaphenocrysts. Despite this loss of stability, olivine megaphenocrysts are found as reacting relics in appreciable quantities in lavas erupted as late as 1947 and are found in small numbers in most of the specimens erupted after 1947. There is even a suggestion in the graph of figure 98 and estimates of olivine in other thin sections that the volume percentage of olivine megaphenocrysts increases slightly from specimen to specimen of the ejecta from 1943–47. Taken together with the sudden decrease during the latter part of 1947, this might be interpreted as indicating that there had been a progressive concentration of intratelluric olivine in the portions of the magma erupted successively between 1943 and 1947 and an impoverishment in those portions of the magma erupted late in 1947. This latter in fact is supported by the chemical relationships, to be discussed more fully below, and there seems to be no basis for proposing that the olivine disappeared simply by reaction to form orthopyroxene, even though that process was operating. It is possible that the sharp break in 1947 in the olivine content may be related to some mechanism permitted by a flank rather than apical outlet of the magma chamber, as will be suggested at a later point in the discussion.

The first appearance of fine-grained orthopyroxene reaction rims on olivine megaphenocrysts was not accompanied by the appearance of orthopyroxene megaphenocrysts. Orthopyroxene microphenocrysts are found in occasional specimens as early as 1943, but megaphenocrysts do not appear until the latter part of 1947 and then only in small numbers. In subsequently erupted specimens successively greater numbers of orthopyroxene megaphenocrysts are found, and these are generally of larger size in the later specimens. Indeed, there is a remarkably consistent tendency towards increase in maximum size of orthopyroxene crystals, starting with the microlites and microphenocrysts of the early ejecta; and in many specimens there appears to be no sharp line of demarcation in size-frequency distribution between the orthopyroxene megaphenocrysts and microphenocrysts. The tiny crystals of opaque oxide found as inclusions in most of the olivine and orthopyroxene megaphenocrysts in spite of their small size should be mentioned here, because their origin is intratelluric also.

Summarizing the relationships of the megaphenocrysts, it is inferred that in those portions of the magma erupted during 1943 and the first part of 1944 olivine, plagioclase, and magnetite were in equilibrium with the liquid at depth. In those portions of the magma erupted during the rest of 1944 and during parts of 1945, only olivine and magnetite were in equilibrium. In those portions erupted during the other parts of 1945 and during 1946 to 1950, olivine no longer was in equilibrium; and that already formed was reacting to form orthopyroxene, not as homogeneous single-crystal shells around the olivine but as matted mantles of crystals of microphenocryst size.

### MICROPHENOCRYSTS

Whereas plagioclase is of very limited occurrence as megaphenocrysts, it is abundant as microphenocrysts in all specimens of the Parícutin ejecta, as shown in figure 99. Olivine, clinopyroxene, orthopyroxene, and, in most specimens, opaque oxide occur together with the plagioclase as microphenocrysts in the groundmasses of most specimens of 1943 lava; but clinopyroxene microphenocrysts are present in only a few specimens erupted after 1943. Olivine "microphenocrysts" (irregular grains) in most of the ejecta of 1944–46 are obviously reacting to form orthopyroxene, and olivine microphenocrysts are not found in the material erupted after 1946. Orthopyroxene microphenocrysts, on the other hand, are generally present in the ejecta of 1944 and subsequently although in some of the early ejecta they are so small that it becomes a matter of judgment whether to class them as microphenocrysts or microlites. It is clear that the development of orthopyroxene is partly at the expense of the olivine in the microphenocrysts and that broadly at least it is a result of the olivine-orthopyroxene reaction relation.

The clinopyroxene microphenocrysts of the early ejecta have been presumed, on the basis of their high extinction angles, to be augitic; and their association with orthopyroxene would fit with the suggestion of Poldervaart and Hess (1951, fig. 6) that augitic pyroxenes should form a reaction series separate from that of olivine-orthopyroxene.

It is of interest, however, to inquire why clinopyroxene largely ceased to form as microphenocrysts in the magma erupted after 1945, while orthopyroxene continued to be formed in all subsequently erupted portions. With progressive crystallization in a homogeneous liquid, it would seem that "augitic" clinopyroxene should continue to crystallize along with orthopyroxene (or pigeonite) at least until the edge of the two-pyroxene field was reached. The fact that the "augitic" phase drops out without significant progress across the two-pyroxene field would therefore lead one to suspect that external factors were involved; that is, the temperature had risen, or the magma was not truly homogeneous, and crystallization was proceeding in successively unlike portions of the magma. The possibility of increase of temperature seems remote because of the lack of appropriate effects on the megaphenocrysts. The few reliable temperature measurements that have been made on the lavas of Parícutin indicate that there has probably been a small but general decrease in temperature of successively erupted materials. In December 1944 the temperature of flowing lava 5 kilometers from the vent was found by Zies (1946, p. 179) to be 1,110° C by use of a thermocouple. During November 1945 to February 1946, a series of thermocouple measurements by Krauskopf (1948b, p. 1272) gave a maximum of 1,070° C at the vent. During October and November 1946, measurements by the writer with an optical pyrometer in subdued daylight gave a maximum of 1,040° C for flowing lava half a kilometer from the vent. The more favorable possibility seems to be that change of composition by progressive contamination of the liquid was the cause of the anomalous crystallization sequence.

From the relationships of the microphenocrysts, we may conclude that, during extrusion and perhaps prior to extrusion, the magma of most of the specimens erupted in 1943 and the first part of 1944 was precipitating plagioclase, olivine and opaque oxide and in addition, orthopyroxene in some portions. In some specimens of pumice such as that erupted in April 1944 (see pl. 10, fig. 2), the microphenocrysts are fresh olivine and plagioclase, which shows that no significant amount of pyroxenes had crystallized prior to leaving the conduit. In much of the magma erupted during the latter part of 1944 and in 1945, clinopyroxene had been crystallizing only in small quantities while plagioclase and orthopyroxene had been forming consistently and olivine had become unstable in certain portions of the magma. In the magma being erupted during and after 1946, the only actively forming crystals were plagioclase and orthopyroxene, with the exception of some erupted in 1946 in which clinopyroxene was formed sporadically.

### MICROLITES AND GLASS

In some cases, especially in lava in the central portions of the thicker flows, crystallization no doubt continued at about the same rate as it had in the conduit and resulted in no marked change in texture to mark the new generation. Most of the specimens of the Parícutin ejecta, however, have been collected from the margins of flows or from bombs, and in such situations the chilling is rapid enough to produce a recognizably finer grained or glassy mesostasis. Glass composes as much as 40 percent of the volume of some specimens examined, while in only a very few was it found to be less than 5 percent of the volume.

Since the formation of microlites is complexly involved in the initial stages of congelation of the glass, the mineral type, habit, and abundance of the microlites must be expected to vary greatly according to the rate of chilling and the many other highly variable factors affecting nucleation. Both orthopyroxene and clinopyroxene are found as microlites in many of the specimens, and the thin flanking plates and swallow-tail extensions of clinopyroxene on orthopyroxene microphenocrysts (pl. 10, fig. 6) are regarded as belonging to this final generation of microlitic development, as are the opaque oxide crystallites scattered through the glass and adhering to the pyroxene of some specimens. Whereas microphenocrysts of clinopyroxene do not generally occur in rocks erupted after 1945, microlites of clinopyroxene are commonly found in most rocks erupted until the end of 1950, although in decreasing amounts. In these conditions of formation the crystalline products may be stable or metastable forms, and the mineral association means little in regard to equilibrim relationships. Calcic plagioclase is not well represented as microlites, and it may be that the flanking plates and microlites of clinopyroxene are calcic pyroxene, the crystallization of which in the rapidly changing conditions was easier than that of calcic plagioclase.

## CHEMICAL RELATIONSHIPS

It can be granted at once that the Parícutin lavas had their source in a single magma chamber, and this offers an advantage not ordinarily present in an inquiry into the mode of origin of a volcanic suite. In the usual study, specimens come from various vents that had been active at widely separated intervals, thus quite probably from different chambers or from different parts of a master chamber at quite different stages of evolution. In contrast, the blood relationship between the members of the Parícutin suite must be very close, with proportionately less variability in the factors of time, space and environmental conditions.

A rigorous treatment would demand that all conceivable modes of origin be examined for their possible contributions to the observed features of the chemistry of the Parícutin igneous suite. The writer is not prepared to give such a rigorous treatment here but rather will consider only two possible modes of origin that have already been suggested: that of fractional crystallization and that of "bodily" assimilation of country rock involving no significant differential movement of chemical constitutents.

Schmitter (1945, p. 130) has concluded that the presence of orthopyroxene in the groundmasses of the 1943 lavas may be a result of assimilation of monzonitic country rock such as represented by the xenoliths. Although the percentage of $Al_2O_3$ in the Parícutin xenoliths is less than in the lavas (see tables 2 and 3), the ratio of $Al_2O_3$: CaO is much higher. Thus the addition of xenolithic material to the magma may have forced the crystallization of orthopyroxene rather than clinopyroxene for much the same reasons as suggested by Bowen (1928, p. 208–210) and others in the case of assimilation of aluminous sediments. Similarly, the presence of orthopyroxene in certain lavas of Hakone volcano is attributed by Kuno (1950, p. 998) to assimilation of granitic wall rock, the low content of normative Wo and high content of water in which is regarded as favoring crystallization of orthopyroxene rather than clinopyroxene in the contaminated magma.

Williams (1950, p. 270) in discussing the whole of the igneous suite of the Parícutin region, including only the lavas erupted from Parícutin volcano in 1943 and 1944, found no reason to doubt that the major control was fractional crystallization and no proof that the course of differentiation had been influenced by contamination of the magma by country rock. Based on tests of the much more complete chemical and petrographic data now available, however, it is concluded here that neither assimilation nor fractional crystallization acting alone could have produced the suite of lavas of Parícutin volcano but that assimilation and fractional crystallization acting together could have produced it. In the following discussion the ability of these two mechanisms to produce the chemical and petrographic trends will be considered first and the thermal and other requirements of the proposed mechanism second.

To test the adequacy of fractional crystallization and assimilation as factors in the production of the observed chemistry of the Parícutin lava, the variation diagram will be the main tool. Starting with any one of the bulk analyses, which for this purpose may be presumed to represent the composition of the magma (including suspended crystals) before eruption, one may determine graphically whether removal or addition of appropriate materials could have produced the compositions of the other lavas. It should be noted that for the tests made here we are not attempting to delineate a liquid line of descent of the magma (Bowen 1928, p. 92) but rather a "bulk line of descent." If, for instance, the graphically determined line of descent simulating fractional crystallization matches that of the plotted analyses, the conclusion would be that fractional crystallization could have been the causal mechanism—if a close match is not obtained it could not have been the sole mechanism. Similar reasoning would apply to the tests of assimilation alone and of assimilation together with fractional crystallization.

Of the several types of variation diagrams in common use, the most practical for the purpose at hand appears to be the conventional silica-variation diagram of the form proposed and applied by Harker (1900, p. 390; 1909, p. 118–146 and 333–350). This diagram has the advantages of ease of construction, simplicity of chemical relationships, and straightforwardness in the graphical addition or subtraction of components from a given material. The objection that errors in analytical determinations of silica may give a false impression of departures from an otherwise smooth trend (Larsen, 1938, p. 506) does not hold in the case of the Parícutin suite, in which all but one of the analyses were made by analysts under the supervision of the same chemist; and therefore, if silica percentages are in error at all, they are probably in error by similar magnitudes in the same direction.

While it would be possible to use other types of variation diagrams here, all are less convenient than the silica-variation diagram. Besides requiring preliminary calculations the diagram of Niggli (Niggli and Beger, 1923, p. 197, 297), in which the molecular values *al*, *fm*, *c*, and *alk* are plotted as ordinates against *si* as abscissa, obscures the relations of iron and magnesia to silica and to each other by combining both into the index *fm*. This diagram likewise obscures the interrelations of soda and potash by combining into the index *alk*. Further, the geometry of the diagram, and hence the graphical operation, is complicated by the manner in which the abscissa, *si*, is calculated. Thus, the *si* value of a mixture of equal parts of materials A and B does not lie half way between the separate *si* values of A and of B.

The variation diagram proposed by Larsen (1938, p. 506), while fulfilling most of the geometric requirements, involves several arbitrary preliminary calculations and has so complex an abscissa that interpretation becomes difficult. In that diagram the weight percent of each oxide constituent is plotted as ordinate against the index $\frac{1}{3} SiO_2+K_2O-FeO-MgO-CaO$, a rough indication of the "acidity" or "basicity" of the rock. When plotted in this manner, almost all igneous rock suites conform more closely to smooth curves than when plotted against silica alone; and this is put forward, somewhat circuitously, as an advantage of the method. Actually, the artificial expedient of loading the abscissa with the same constituent that is being plotted as ordinate cannot help but give greater conformance of plotted points to smooth lines, the extreme case, of course, being the straight line obtained by plotting one constituent against itself. The writer doubts that such deemphasis is justified in the usual case and certainly not in the carefully analyzed Parícutin lava series in which divergences from smooth chemical trends are significant and should be explained rather than deemphasized.

The general chemical setting of the lavas of Parícutin can be best illustrated on a small scale, silica-variation diagram, such as figure 103, which shows the relationships between the lavas, their phenocrysts (olivine, orthopyroxene, and plagioclase), and their xenolithic inclusions. The megaphenocryst compositions used here are olivine, $Fo_{80}$; orthopyroxene, $En_{75}$; and plagioclase, $An_{70}$, the plagioclase being taken as somewhat more calcic than the optically determined microphenocrysts. The effects of possible departures from these assumed compositions will be considered later. The four analyses of xenoliths have been combined to give a plotted position of the "average xenolith," to be used in the following discussion as an approximate representation of the xenolithic material. On the variation diagram at this scale, the lavas form a close-knit series in the middle silica range, whereas their olivine and plagioclase phenocrysts lie at lower silica percentages, their orthopyroxene phenocrysts within the silica range of the lavas, and their xenoliths in a much higher silica range.

As an example on figure 103, the simple subtraction of olivine, $Fo_{80}$, from the bulk analysis of no. 12 gives successive compositions lying along straight line extensions away from the corresponding oxide constituents of the olivine. In the residuum silica, alumina, lime, soda, and potash are seen to increase while iron and magnesia decrease. At

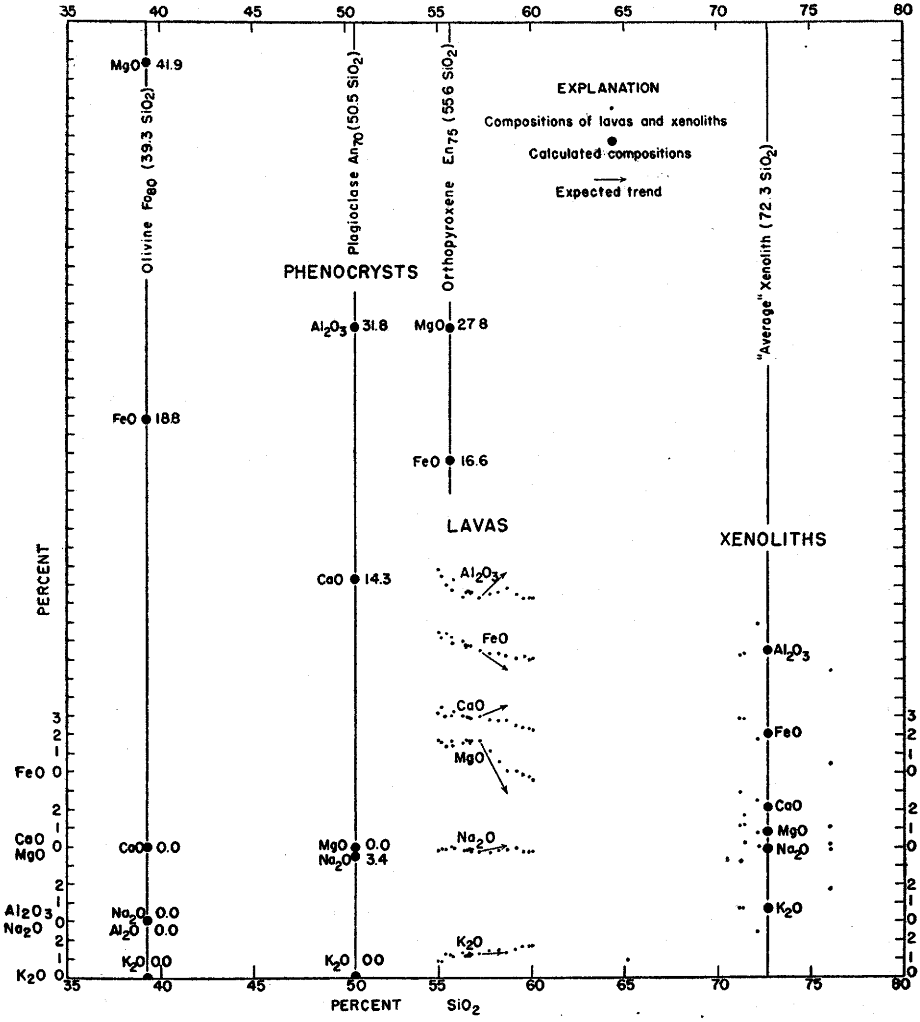


FIGURE 103.—Silica-variation diagrams of lavas, phenocrysts, and xenoliths of Parícutin volcano. Dots represent bulk compositions of lavas and xenoliths (analyses 6–10 averaged). Values for bulk compositions are counted from 0 point for each oxide at bottom of scale. Arrows from analysis 13 show trends to be expected by simple subtraction of olivine, $Fo_{80}$, from mixture of composition of no. 12. Heads of arrows are at silica percent of analysis 15.

a given silica percentage, say that of analysis 15 (58.6 percent silica), the content of the other oxide constituents in the residuum can be read off; and it is found that they do not even approximate the values for corresponding constituents of no. 15. The conclusion is that simple removal of olivine, $Fo_{80}$, alone from the magma represented by analysis 12 could not have produced the magma represented by no. 15. By similar operations it can be shown that no pairs of Parícutin lavas can be related by simple addition or subtraction of olivine, $Fo_{80}$, alone or of plagioclase, $An_{70}$, alone.

To test the effects of simultaneous addition or withdrawal of two mineral constituents, such as olivine and plagioclase, one may proceed as illustrated at the left in figure 104, an enlargement of the central portion of figure 103. Whereas only one oxide control, silica, was needed for the subtraction of a single mineral constituent, here two will be required; and for these, silica and alumina have been chosen arbitrarily. The pair of specimens to be compared are taken as no. 1 and no. 11, and just enough olivine and plagioclase have been removed from no. 1 to attain the silica and alumina percentages of no. 11. The graphical procedure is as follows: A radius is drawn from the alumina point of olivine (outside of the diagram) through the alumina point of analysis 1, and another radius is drawn from the alumina point of plagioclase through the alumina point of analysis 11. The intersection of these radii at 55.5 percent silica determines the relative proportions of olivine and plagioclase subtracted. A radius is drawn from the FeO point of olivine through the FeO point of no. 1; the radius then intersects the 55.5 percent silica-vertical at 7.0 percent FeO. Through this point a radius is drawn from the FeO point of plagioclase and, extended, it intersects the $SiO_2$ vertical of no. 11 at 8.2 percent FeO, about 1.3 percent higher than the plotted value of FeO in no. 11. In a similar manner it is found that the test value of CaO is too low by 0.8 percent and that of MgO is too low by 0.3 percent. From the large discrepancies in both FeO and CaO it may be concluded that simultaneous subtraction of $Fo_{80}$ and $An_{70}$ does not account wholly for the differences in composition between no. 1 and no. 11.

It should be noted that it does not matter which constituent, olivine or plagioclase, is subtracted first. The test is equally valid if performed in reverse, that is, by addition of olivine and plagioclase to no. 11, for it leads to the same relative discrepancies in MgO, CaO and FeO upon duplicating the $SiO_2$ and $Al_2O_3$ values of no. 1. In fact, one may start with any member of the related series of rocks in this narrow range of silica content and test the correspondence of any or all of the others of the series to the graphically determined compositions. Because there is no compelling reason to insist that the least silicic of the lavas (no. 1) represents the direct parent of the others, one may choose an intermediate member as a convenient point of departure from which to test the entire series, keeping in mind that the procedure is justified whether the lavas are direct derivatives of the previously erupted lavas or all derived from a common parent.

The right hand portion of figure 104 illustrates the graphical operations in adding or subtracting three materials, here olivine, $Fo_{80}$; plagioclase, $An_{70}$; and "average xenolith." Although the constructions are more tedious than those for only two variables, the solution again is unique and essentially unaffected by the sequence in which the operations are performed. It is seen that, with three materials available for addition or subtraction, three oxide controls must be used, and for these silica, alumina, and magnesia have been chosen.

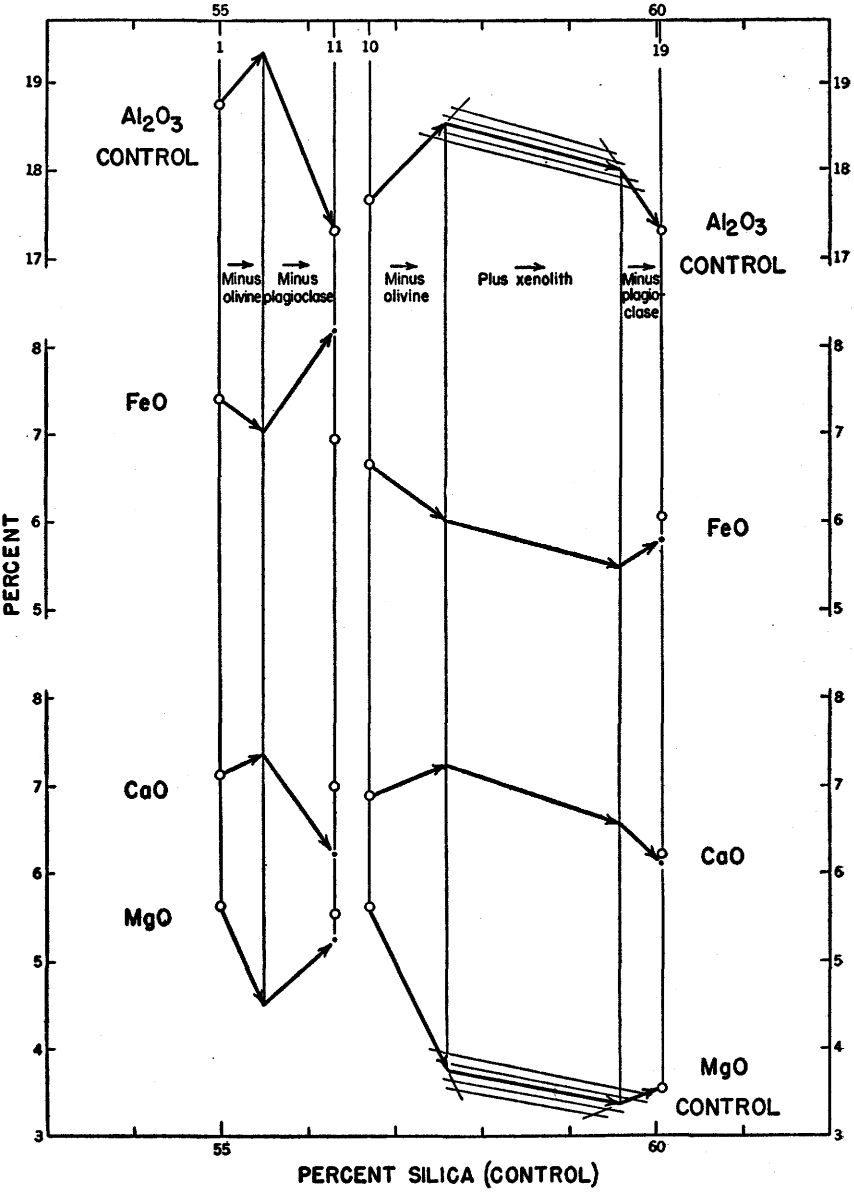


FIGURE 104.—Silica-variation diagrams, showing graphical operations in addition and subtraction of materials from bulk compositions (represented by open circles) of lavas of Parícutin volcano. Dots opposite FeO, CaO, and MgO of no. 11 show percentages in final product subtracting olivine, $Fo_{80}$, and plagioclase, $An_{70}$, from no. 1, using $SiO_2$ and $Al_2O_3$ of no. 1 and no. 11 as controls. Dots opposite FeO and CaO of no. 19 show percentages in final product obtained by subtracting olivine, adding "average xenolith," and subtracting plagioclase from no. 10, using $SiO_2$, $Al_2O_3$, and MgO of nos. 10 and 19 as controls.

Using analysis 10 as the starting material and no. 19 as the end material, radii are drawn from the alumina point of olivine through the alumina point of no. 10 and from the magnesia point of olivine through the magnesia point of analysis 10. Similarly, radii are drawn from the alumina and magnesia points of plagioclase respectively through the alumina and magnesia points of analysis 19. Then a series of closely spaced radii are drawn from the alumina and magnesia points of the "average xenolith," cutting the olivine and plagioclase radii. One may then choose the radii, one from xenolithic alumina and the other from xenolithic magnesia, which intersect the olivine and plagioclase radii at corresponding silica percentages (here 57.6 percent and 59.6 percent silica). A radius from the FeO point of olivine through the FeO point of analysis 10 cuts the 57.6 percent silica-vertical at 6.0 percent FeO, and a straight line from this point towards the FeO point of the "average xenolith" cuts the 59.6 percent silica-vertical at 5.5 percent FeO. A straight line from this point through the FeO point of plagioclase cuts the silica-vertical of analysis 19 at 5.8 percent FeO, about 0.3 percent lower than the actual plotted value for the FeO of analysis 19. By a similar procedure the CaO content of the graphically derived product is found to be 0.1 percent lower than that of analysis 19.

Here again the magnitudes of the discrepancies between graphically determined end points and their actual counterparts may be taken as a measure of the ability, from the compositional standpoint only, of the process under test to account for the derivation of the end material from the starting material or of both from a common parent. In this example the total discrepancies for the four oxides, $Al_2O_3$, FeO, CaO, and MgO, is 0.40 percent; and one may speak of an average discrepancy here of 0.10 percent. Another useful measure of the chemical feasibility of the graphically simulated process is the amount of divergence from the actual "trend" between starting and end materials, and in this example the divergence for the four tested oxides may be expressed as 0.03 percent per percent change of silica between analyses 10 and 19.

The results of testing the olivine-plagioclase-xenolith variables two at a time are shown in figure 105, and those of the complete combination in figure 106, all tests using analysis 10 as the starting point. In both figures the open circles represent the plotted points of the bulk analyses, and the filled circles represent the compositions of materials derived graphically from no. 10 by using the different combinations. Soda and potash have been left out of the diagrams on the assumption that, no matter what combinations are used, their test points will fall near the actual points because the soda and potash contents of all the materials, lavas as well as phenocrysts and xenoliths, are low and nearly in line with each other on the diagram.

On figure 105 the closest conformance to the actual plotted points is obtained in the test of the olivine-xenolith combination (points con-

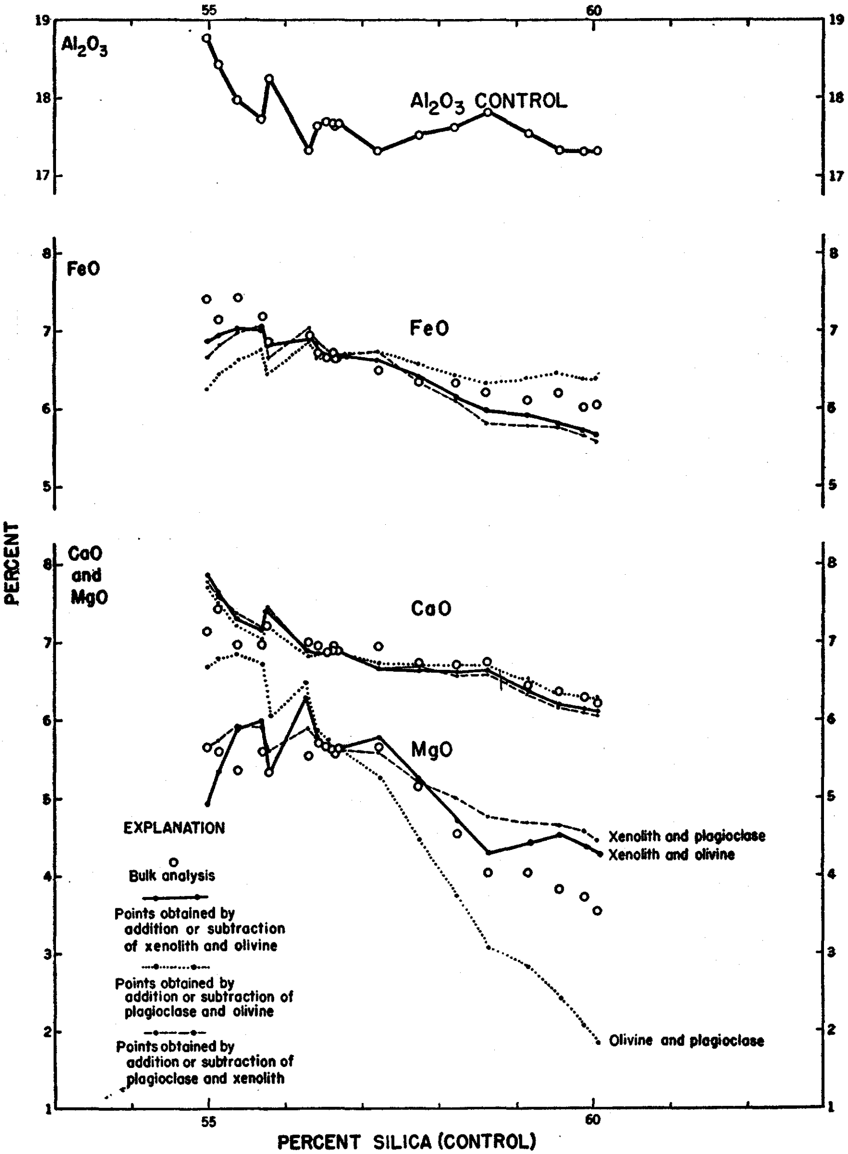


FIGURE 105.—Silica-variation diagram comparing actual bulk compositions (open circles) with trends developed by graphical addition or subtraction of olivine, plagioclase, and xenolithic material two at a time, from analysis 10 (tables 2 and 3), using $SiO_2$ and $Al_2O_3$ as controls. Dotted lines connect points obtained by fractional crystallization involving olivine, $Fo_{80}$, and plagioclase, $An_{70}$. Dashed lines connect points obtained by assimilation of xenolithic material and fractional crystallization of plagioclase, $An_{70}$. Solid lines connect points obtained by assimilation of xenolithic material and fractional crystallization of olivine, $Fo_{80}$.

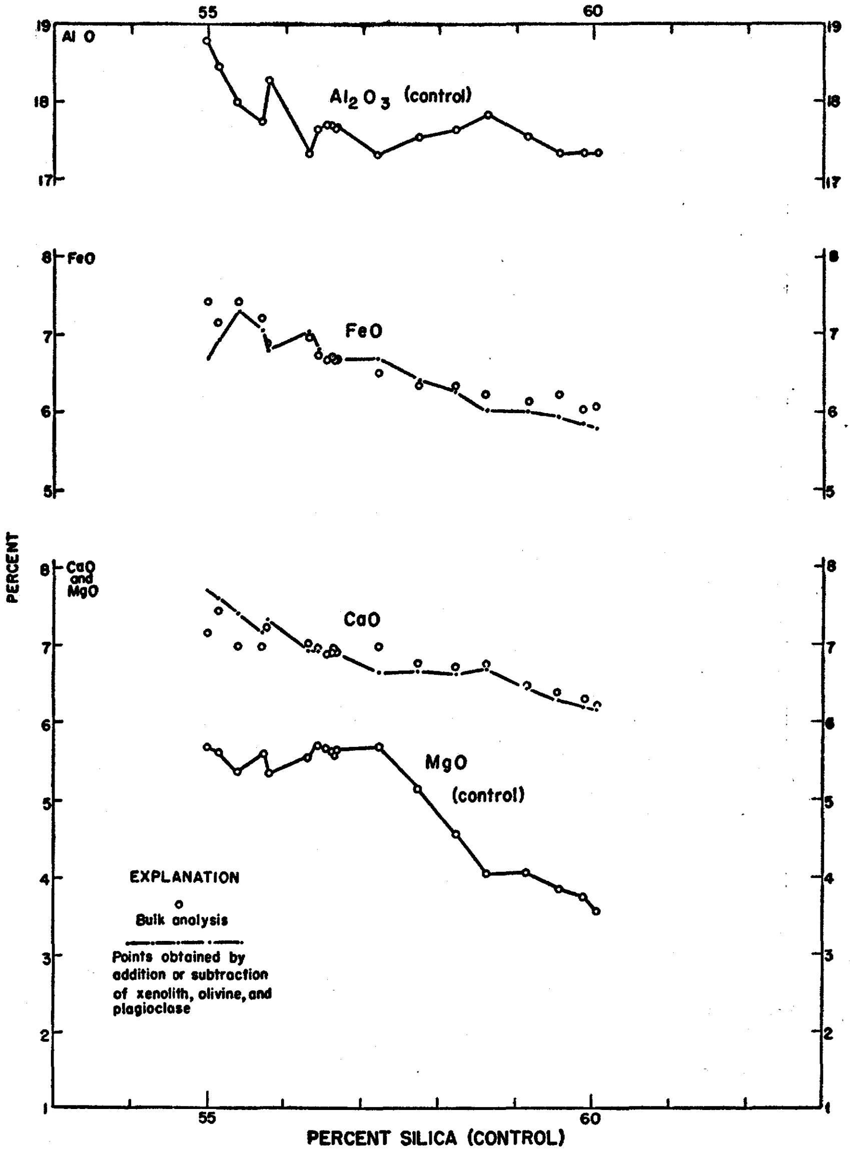


FIGURE 106.—Silica-variation diagram comparing actual bulk compositions of Parícutin lavas (open circles) with trends developed by graphical addition or subtraction of olivine, plagioclase, and xenolithic material from analysis 10 (table 2), using $SiO_2$, $Al_2O_3$, and MgO as controls.

nected by solid line). Even here the discrepancies are considerable and erratic at the low-silica end of the diagram. Although the discrepancies reach nearly the same magnitude at the high-silica end, for iron and magnesia the rough parallelism over certain portions of the silica range appears to be significant. The olivine-plagioclase combination, on the other hand, gives trends (dotted lines) from no. 10, which diverge widely from the actual trends of magnesia and iron at the low-silica portion and from that of magnesia at the high-silica end. The divergence is so marked that one must conclude that addition and subtraction of olivine and plagioclase could not have been an effective process by itself in producing the lava series.

The test points of the plagioclase-xenolith combination (connected by dashed lines in fig. 105) diverge somewhat more from the actual points of magnesia and iron than do those of the olivine-xenolith combination. In the high-silica range they fall on the opposite side of the actual points from the test points of the olivine-plagioclase conbination. Although the graphic test is valid in itself, the plagioclase-xenolith combination is of dubious physical significance, because it excludes olivine, which is much more abundant as phenocrysts in the lava and seemingly more subject to gravitational movement in the magma than plagioclase. This and the appreciable individual discrepancies of the plagioclase-xenolith test points furnish a basis for strong doubt that addition or subtraction of only plagioclase and xenolithic material could account for the chemistry of the lava series.

Figure 106, at the same scale as the preceding figure, shows the results of simultaneous additions or subtractions of all three variables, olivine, plagioclase, and average xenolith from analysis 10. The disprepancies in FeO are generally less than in any of the paired-variable tests, most of them less than one-fourth of 1 percent and probably approaching the combined margin of error of analysis, graphical plotting, and spurious effects. As in the previous tests, the discrepancies in CaO are generally negligible, at least for the high-silica portion. The conformance is sufficiently good to justify the conclusion that combined action of both fractional crystallization and assimilation processes—which involve olivine, $Fo_{80}$; plagioclase, $An_{70}$; and "average" xenolith—could have been the major cause of chemical differences between the lava of analysis 10 and the higher silica members of the series. From the standpoint of bulk of material involved, assimilation would appear to have been the predominant process.

While the results of the foregoing tests appear to argue against fractional crystallization as the only process involved, they are based on but one set of compositions for the participating intratelluric olivine and plagioclase, $Fo_{80}$ and $An_{70}$. In view of the uncertainty surrounding the exact compositions of the intratelluric crystals, it is desirable to test other combinations of olivine and plagioclase, as well as the possible effect of participation of orthopyroxene and magnetite. Such tests have been made, first for all combinations of $Fo_{70}$, $Fo_{75}$, $Fo_{80}$, and $Fo_{85}$ with $An_{60}$, $An_{70}$, and $An_{80}$; then for combinations of magnetite-bearing olivine with plagioclase; for combinations of magnetite as a free variable with olivine and plagioclase; and finally for combinations of orthopyroxene with plagioclase and with olivine

The results of these graphic tests and others are summarized in table 9, where average "divergences" of test trends from actual trends are tabulated. In calculating the average divergence for a particular oxide the ordinate distance between each test point and actual point was divided by the abscissa distance between test point and starting point (analysis 10) without regard for algebraic sign. The resulting quotients for points to the left of the starting point were averaged separately from those to the right and listed for each oxide. Test points for analyses 6, 8, and 9 were not included because of the close approach of these analyses to analyses 7 and 10. The left and right divergences of all four oxides were then averaged and listed, as were the over-all average divergences for the whole series. The numbers so obtained express the average percent divergence per percent change of silica content through the series and thus measure the ability of each tested combination to reproduce the observed chemical trends. Although it would be difficult to prescribe limits, an over-all average divergence of greater than 0.15 percent per percent change of silica would seem to be too great to permit acceptance of the particular combination as feasible, while one between 0.10 and 0.15 would cast doubt on the feasibility of the combination. A combination whose over-all average divergence is less than 0.10 might be regarded as quite promising, and an over-all average divergence of less than 0.05 might be regarded as indicating an exceptionally close match, in view of the possible unsystematic variables involved.

In table 9 the over-all average divergences for all combinations of olivine and plagioclase tested range from 0.18 to 0.38, all too high by the above standards to allow acceptance of these combinations as feasible. The over-all average divergences of the magnetite-bearing olivine (magnetite as inclusions in olivine in ratio of 5:95 by weight) in combination with plagioclase are 0.20 and 0.24, likewise too high. Those of the freely variable plagioclase-olivine-magnetite combinations are 0.13, making this combination possibly feasible from the standpoint of the chemical variation alone. In attaining this low-value of divergence, however, the differential movement of from one-quarter to one-half as much magnetite as olivine is implied by the graphical construction. This is regarded as definitely unrealistic in view of the observed lack of significant amounts of movable magnetite in the rocks themselves and in view of the physical chemical arguments against such large amounts of magnetite being able to crystallize from a magma of this type.

TABLE 9.—*Average divergences of test trends from actual trends of the Parícutin silica-variation diagram*

[Expressed as percent divergence per percent change of silica content. Starting point in all cases is analysis 10]

| Combination tested graphically [1] | Average divergence of individual oxides | | | | | | | | Average divergence of the four oxides | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Al_2O_3$ | | FeO | | CaO | | MgO | | to left | to right | over-all |
| | to left | to right | to left | to right | to left | to right | to left | to right | | | |
| $An_{70}$ alone | 2.21 | 1.79 | 1.56 | 1.10 | 1.02 | 0.95 | 0 91 | 1.23 | 1.42 | 1.27 | 1.34 |
| $Fo_{80}$ alone | 1.21 | .98 | .27 | .41 | .64 | .43 | 2.18 | 1.27 | 1.08 | .77 | .92 |
| Xenolith alone | .37 | .14 | .19 | .06 | .06 | .16 | .39 | .26 | .23 | .16 | .20 |
| $Fo_{70}$–$An_{60}$ | 0 | 0 | .26 | .19 | .12 | .12 | .88 | .20 | .32 | .13 | .22 |
| $Fo_{70}$–$An_{70}$ | 0 | 0 | .25 | .19 | .19 | .10 | .75 | .18 | .30 | .12 | .20 |
| $Fo_{70}$–$An_{80}$ | 0 | 0 | .24 | .17 | .15 | .10 | .69 | .12 | .27 | .10 | .18 |
| $Fo_{75}$–$An_{60}$ | 0 | 0 | .31 | .10 | .12 | .12 | .92 | .32 | .34 | .13 | .23 |
| $Fo_{75}$–$An_{70}$ | 0 | 0 | .29 | .11 | .15 | .10 | .87 | .28 | .33 | .12 | .22 |
| $Fo_{75}$–$An_{80}$ | 0 | 0 | .27 | .11 | .14 | .10 | .84 | .22 | .31 | .11 | .21 |
| $Fo_{80}$–$An_{60}$ | 0 | 0 | .45 | .17 | .12 | .13 | 1.12 | .47 | .42 | .19 | .30 |
| $Fo_{80}$–$An_{70}$ | 0 | 0 | .41 | .14 | .20 | .10 | 1.03 | .38 | .41 | .15 | .27 |
| $Fo_{80}$–$An_{80}$ | 0 | 0 | .38 | .12 | .14 | .10 | .93 | .32 | .36 | .13 | .24 |
| $Fo_{85}$–$An_{60}$ | 0 | 0 | .64 | .31 | .13 | .13 | 1.29 | .61 | .51 | .26 | .38 |
| $Fo_{85}$–$An_{70}$ | 0 | 0 | .53 | .27 | .16 | .10 | 1.24 | .56 | .48 | .24 | .35 |
| $Fo_{85}$–$An_{80}$ | 0 | 0 | .50 | .22 | .17 | .10 | 1.16 | .46 | .46 | .20 | .32 |
| $An_{70}$–(Mgt $Fo_{75}$)* | 0 | 0 | .25 | .16 | .25 | .10 | .77 | .16 | .32 | .10 | .20 |
| $An_{70}$–(Mgt $Fo_{80}$)* | 0 | 0 | .35 | .10 | .25 | .10 | .92 | .25 | .38 | .11 | .24 |
| $En_{75}$–$An_{70}$ | ------ | 0 | ------ | .10 | ------ | .16 | ------ | .74 | ------ | .25 | -------- |
| $En_{70}$–$Fo_{80}$ | ------ | 0 | ------ | .33 | ------ | .12 | ------ | .33 | ------ | .19 | -------- |
| $En_{75}$–$Fo_{80}$ | ------ | 0 | ------ | .12 | ------ | .10 | ------ | .16 | ------ | .09 | -------- |
| $En_{80}$–$Fo_{80}$ | ------ | 0 | ------ | .05 | ------ | .09 | ------ | .11 | ------ | .06 | -------- |
| Xen–$An_{70}$ | 0 | 0 | .27 | .15 | .29 | .12 | .32 | .20 | .22 | .12 | .17 |
| Xen–$Fo_{70}$ | 0 | 0 | .26 | .17 | .26 | .11 | .40 | .14 | .23 | .11 | .17 |
| Xen–$Fo_{80}$ | 0 | 0 | .18 | .10 | .26 | .11 | .55 | .14 | .25 | .09 | .16 |
| Xen–$Fo_{85}$ | 0 | 0 | .21 | .08 | .23 | .14 | .58 | .11 | .26 | .08 | .16 |
| Xen†–$Fo_{80}$ | 0 | 0 | .25 | .06 | .26 | .09 | .60 | .09 | .28 | .06 | .16 |
| $An_{70}$–$Fo_{80}$–Mgt | 0 | 0 | .48 | .24 | .22 | .10 | 0 | 0 | .15 | .09 | .13 |
| $An_{70}$–$Fo_{85}$–Mgt | 0 | 0 | .53 | .21 | .17 | .10 | 0 | 0 | .17 | .08 | .13 |
| Xen–$Fo_{80}$–Mgt | 0 | 0 | .54 | .06 | .31 | .15 | 0 | 0 | .21 | .05 | .13 |
| Xen–$Fo_{80}$–$An_{60}$ | 0 | 0 | .20 | .10 | .21 | .12 | 0 | 0 | .10 | .05 | .07 |
| Xen–$Fo_{80}$–$An_{70}$ | 0 | 0 | .23 | .09 | .21 | .13 | 0 | 0 | .11 | .05 | .08 |

[1] An=anorthite; Fo=forsterite; En=enstatite; Mgt=magnetite; Xen=average xenolithic material.
*Ratio of olivine to magnetite, 95 to 5 by weight.
†FeO 1 percent higher, $Al_2O_3$ 1 percent lower than in "average" xenolith.

The divergences of trends of orthopyroxene-plagioclase combinations are similar to or somewhat greater than those of the corresponding olivine-plagioclase combinations, at least for that portion of the lava series to the right of analysis 10 on the variation diagram. Because of the proximity of orthopyroxene to the lavas lower in silica than no. 10 (see fig. 103), the graphical constructions must be performed with great care to avoid large errors; and if the silica content of the orthopyroxene is the same as that of the lava being compared, the graphical procedure becomes indeterminate with silica as the abcissa. The low-silica portion of the lava series has been left out of consideration here because of this and because the lack of orthopyroxene megaphenocrysts in those lavas make it unlikely that movement of orthopyroxene crystals was involved in their derivation. As an example of the results to be expected in tests of the orthopyroxene-plagioclase combinations, the combination, $En_{75}$–$An_{70}$ is listed in table 9 and shows a 4-oxide average divergence of 0.25 percent per percent change of silica to the right of analysis 10. Exploratory tests of the other combinations of $En_{70}$, $En_{75}$, and $En_{80}$ with $An_{60}$, $An_{70}$, and $An_{80}$ indicate that their 4-oxide divergences would be similarly large. It is therefore concluded that the orthopyroxene-plagioclase combinations cannot be used to account for the chemical relationships of the high-silica portion of the lava series.

The results of tests of three orthopyroxene-olivine combinations are given in table 9 for that part of the lava series to the right of analysis 10 on the diagram. The 4-oxide average divergence of the combination $En_{80}$–$Fo_{80}$ is 0.06, that of $En_{75}$–$Fo_{80}$ is 0.09 and that of $En_{70}$–$Fo_{80}$ is 0.19 percent per percent change of silica, indicating that the first two combinations permit tolerably good matches of the observed trends. But the graphical operations by which such good matches are obtained imply events in the magma that are extremely complicated. To derive a late member of the lava series from no. 10, orthopyroxene must be added in each case while olivine is being subtracted. Starting with 100 grams of no. 10, for instance, one must add 26 grams of $En_{70}$ while subtracting 22 grams of $Fo_{80}$ to approach the composition of no. 19. Tests with the combinations $En_{75}$–$Fo_{80}$ and $En_{80}$–$Fo_{80}$ indicate that similar amounts of the two minerals would be involved. To furnish enough magnesia for continued crystallization of olivine, the orthopyroxene must be continuously fed to and dissolved in the liquid; and the dissolution of the orthopyroxene "xenocrysts" must be complete, for corroded forms are not found in the resulting lavas. Upon approaching the composition of no. 19, the process must be stopped and crystallization of some orthopyroxene phenocrysts accomplished before eruption. It may be assumed furthermore that the trend of intermediate bulk compositions follows something like the trend of the lava series in passing from no. 10 (or from a more distant parent) to no. 19 by this method of differentiation. Thus, after the approximate composition of no. 15 is reached, for instance, some 10 grams of additional olivine must be crystallized and removed while dissolving some 12 grams of orthopyroxene. But this would appear to be impossible, for the petrographic characters of the lavas indicate that olivine was not able to crystallize in the magma of this composition and that orthopyroxene was crystallizing rather than dissolving. These and similar difficulties lead to the conclusion that addition and subtraction of combinations of olivine and orthopyroxene alone, while able to reproduce fairly well the bare chemical trends, cannot be reconciled with the observed petrographic characters of the lava series.

With these tests, all the reasonable combinations that might have been involved in fractional crystallization of the Parícutin magma appear to have been considered and all appear to be infeasible, either from the standpoint of the chemical requirements alone or from the standpoint of the petrography and physical chemistry. The conclusion is drawn therefore that fractional crystallization could not have been the only process producing the lava suite of Parícutín volcano.

The tests of the two combinations of xenolithic material with olivine and plagioclase listed at the bottom of table 9, show over-all average divergences of 0.07 and 0.08, both quite acceptable values, which allow the conclusion that some such combination of assimilation and fractional crystallization can account for at least the chemical requirements imposed by the series. There likewise appears to be nothing in the petrographic characters of the series that would make this combination infeasible. It remains to consider whether the thermal requirements of the implied assimilation could have been met by the Parícutin magma, and this aspect will be discussed in the final section.

The average over-all divergences listed in table 9 may perhaps be taken as the most basic measure of the adequacy of the tested combinations to meet the chemical requirements, since they roughly represent what one might obtain if, instead of arbitrarily using certain oxides as control, an over-all control could be imposed to best suit the combination and the oxide relationships. Nevertheless, the other averages listed are of interest, most notably the consistently greater average divergences to the left of the starting point as compared to those to the right. This is interpreted here as meaning that all the combinations tested account less well for the low-silica lavas than they do for the high-silica lavas. It may be, therefore, that some additional factor has been involved in producing the low-silica rocks even in the case of the xenolith-olivine-plagioclase combination in which the over-all divergence is small. It should be mentioned here also that the individual divergences of certain of the analyses, especially no. 11 and to a lesser extent no. 12, are much larger than those of the other analyses in the tests of many of the combinations, including those of xenolith-olivine-plagioclase. If these combinations are accepted as feasible to account for the series as a whole, an additional factor or factors may be involved in the production of the lavas of analyses 11 and 12.

## THERMAL REQUIREMENTS

The graphical tests in the preceding section indicate that assimilation and fractional crystallization acting together could have produced the chemical features of the erupted lavas. It remains to examine whether sufficient heat energy might have been available to the magma to enable the appreciable amount of assimilation implied by the results of the graphical investigation of the chemistry of the lava series.

The approach to the thermal problem will be to determine the amount of xenolithic material added in changing from the composition of a low-silica member of the series to that of a high-silica member, and from this, the amount of heat demanded by the assimilation of the added material. Because no superheat may be presumed to have been present, the source of heat for assimilation must be looked for in the heat of crystallization of minerals from the magma. Because they are presumed to have already crystallized in its magma, the megaphenocrysts in the starting lava had already spent their heat of crystallization. Any useable heat for assimilation must therefore come from crystallization of the still liquid portion of the magma. As an approximation of the composition of the magmatic liquid, the calculated composition of the groundmass (table 2) will be accepted here, and as a starting material, that of the groundmass of the least silicic lava, analysis 1, will be chosen. The same considerations do not carry the same weight when applied to the end product, nor does it make a great deal of difference in the cases of the high-silica members of the Parícutin series, for their content of megaphenocrysts is very small.

The graphical procedure indicates that addition of 25.4 grams of "average" xenolithic material and subtraction of 2.9 grams of olivine, $Fo_{80}$, and 9.6 grams of plagioclase, $An_{70}$, from 100 grams of the groundmass material of no. 1 will give 112.9 grams of material closely approximating the composition of the groundmass of no. 19. Thus, 25.4 grams of xenolithic material must be assimilated, and the heat required may conveniently be divided into two parts: that necessary to raise the temperature of the quartz monzonitic country rock to that of the magma and that necessary to convert the country rock to a liquid and incorporate it into the magma. It is of not great concern here that the two parts must overlap somewhat in actual operation.

For the first step let it be assumed that the chosen 25.4 grams of quartz monzonite to have been at a depth of about 6 kilometers in the crust, with an initial temperature of about 200° C, determined by a thermal gradient of about 30° C per kilometer and that its temperature is to be raised to 1,100° C. The average heat capacity of quartz monzonite over this indicated temperature range may be assumed to be about 1.1 joules per gram on the basis of data listed for granite by Goranson (1942, table 16–2). Thus, to heat the 25.4 gram mass from 200° C to 1,100° C would require about 25,000 joules. For the second step—that of actually melting and dissolving the granitic material once its temperature has been raised to the melting range—we find that appreciably less heat would be required. The heats of fusion of the common granitic minerals, according to Goranson (1942, table 16–3) are 203 joules per gram for albite, 418 joules per gram for orthoclase, and 244 joules per gram for quartz. For quartz monzonite rock, of the type we are dealing with in the observed xenoliths, a rough value of 250 joules per gram would seem indicated for its heat of fusion. Heats of mixing are of such a low order of magnitude, both positive and negative, that they probably may be neglected. The fusion and solution of 25.4 grams of granitic material, already at its fusion temperature, would thus require about 6,350 joules, and the total heat required to assimilate 25.4 grams of cold quartz monzonite would be about 31,350 joules.

To obtain this amount of heat from the original 100 grams of magma would require the crystallization of so large a proportion of it that its mobility would be lost. From the data listed by Goranson (1942, table 16–3), for instance, the latent heat of crystallization of plagioclase, $An_{70}$, may be estimated as about 370 joules per gram, and that of olivine, $Fo_{80}$, as about 425 joules per gram. Those of the more acid members of the reaction series are generally lower but of the same order of magnitude. To get 31,350 joules, the crystallization of 85 grams of plagioclase alone or 74 grams of olivine alone would be required. Any combination of these or the lower members of the reaction series would not significantly change the total amount of crystallization needed to furnish the desired heat so that one could not expect to have more than about a fifth of the original mass remaining as liquid. This situation, of course, is entirely unrealistic; therefore, the bulk of the required heat must be looked for outside the particular 100 gram unit of liquid chosen here as a starting point.

A mechanism proposed by Holmes (1931) for the upward penetration of simatic and sialic rocks by the fluxing action of magma cupolas (overhead stoping and fluxing of Daly, 1914, p. 194–208; 1933, p. 267–286), which he applied as an explanation of the acidic-basic volcanic complexes of Scotland, appears to offer a basis for the availability of adequate heat, as well as an explanation of other observed relationships at Parícutin volcano, perhaps also of those of the whole Parícutin region. Holmes emphasizes more than Daly the probability that thermal convection can furnish the great quantities of heat needed for the fluxing and stoping of the country rock at the cupola roof. Holmes (1931, fig. 3) first supposes a deep-seated, broad basaltic magma chamber with only slight local irregularities in the roof. Thermal convection currents will tend to start under any slight arch, and once started, will tend to bring hotter magma up to the central part of the arch. Thus, the fluxing action at the apex may begin, slowly at first, but becoming more effective as the arch becomes steeper by solution and removal of the country rock at the apex.

Once under way this process should continue to assimilate the roof rock, and the magma would dissolve out a high-arched cupola in the overlying rock, regardless of the composition of the rock. With a sufficiently large main chamber of the magma below, the cupola may be considered able to flux its way upward through the overlying thick layer of generally basic and intermediate rock and into the sialic layer. While yet in the simatic layer, no great modification of the composition of the cupola magma may be expected by incorporation of roof rock. Once in the sialic layer, however, a tendency towards acidification of the magma of the cupola may be caused by the progressive incorporation of granitic material. Initially much of this granitic material may be expected to be carried down with the basaltic magma along the flanks. But Holmes considers that a point may be reached when the granitic material will not all sink, and at that stage a secondary circulatory system is set up in the upper portion of the cupola that will tend to allow the development of a definitely more granitic phase of the magma separate from the generally basaltic magma below (Holmes, 1931, fig. 4).

It should be remarked that the slow, upward solution-penetration into the country rocks and the development of the slim cupola can be accomplished by the magma even though it be crystallizing and therefore not possessing any superheat in the usually accepted sense. Thus, there is an indefinitely large amount of heat being brought by convection from the hotter main magma chamber below, and one can reason that, because of the great mass of hotter magma available in the main chamber, an entirely adequate amount of heat can be furnished to the cupola as long as the convection is effective. The heat, brought in by convection, is made available by crystallization. It is used in raising the temperature of the country rock and, where mechanically favorable, in incorporating wall rock material into the magma as a liquid.

The limits beyond which such a process ceases to operate may involve the eventual exhaustion of the heat of the main chamber or perhaps, before this, the increase of viscosity of the cupola magma and its acidic "roof magma" to the point that convection is no longer effective. The closer the cupola approaches the surface, the more rapid will be its loss of heat; and with no disturbing factors, it would seem that an economic limit of upward migration would be reached.

Perhaps more effective, however, would be the increasing likelihood of eruption as the cupola roof draws nearer to the surface. The tapping of the cupola and exhaustion of the pent up volatiles, as well as bodily removal of the hot material, must certainly have a cooling effect that, if the cupola development is slowing down anyway, may serve to stop it altogether.

To apply Holmes' mechanism to the explanation of the Parícutin rock suite, the writer has sketched (with some indefiniteness as to actual dimensions) the situation of the imagined magma cupola below the volcano (fig. 107). The cupola is shown slightly offset from a position directly below the vent for somewhat indirect reasons which will be discussed later. The cupola is visualized as a thin upward extension of a much larger, basaltic magma body, the main lateral development of which would be at an appreciable depth, say 20 to 30 kilometers. It is represented as having penetrated upward into the sialic rocks, the base of which, in the absence of data, is assumed to be at a depth of about 12 kilometers. What little regional evidence is available indicates that the sialic rocks here consist chiefly of quartz monzonitic rocks and acidic effusives overlain by the andesitic and basaltic effusives.

The rates of abstraction of heat for the two stages, heating of country rock and dissolution of xenoliths, conceivably would be different and would lead to different rates of crystallization. The heating of the country rock must necessarily be a very slow process, controlled largely by the small thermal conductivity of the rock. The crystals so produced in the magma should be large and capable of gravitative migration. Once the preheated wall rock has been broken off and enters the mass of the magma, it may cause a relatively rapid chilling of the immediate magma and a speeding up of the rate of crystallization, hence production of fine crystals incapable of significant gravitative migration. One does not expect that the subsequently erupted lavas represent the portions of the magma that preheated the country rock, for much of that magma would have moved on past in the convection system. Its large, slowly formed crystals would likewise have moved with it or ahead of it down the flank of the cupola. At least some of the smaller crystals of the lavas, the microphenocrysts for instance, might represent crystals whose formation was caused by the more rapid extraction of heat owing to the presence finally in the magma of the xenolithic and xenocrystic material. To distinguish them petrographically from the crystallization owing to cooling on extrusion of the lava might be difficult or impossible.

The Parícutin magma chamber, or cupola as we will now regard it, is shown in the sketch of figure 107 as offset from the site of the

Parícutin vent on the surface. The reasons for showing it thus are indirect; and such a postulated position must, of course, be regarded as merely conjectural. In the first place, the results of the airborne magnetic survey of the region by the U. S. Geological Survey in December 1947 (J. R. Balsley, personal communication) have shown a strong negative magnetic anomaly of some 200 gammas centering about a point about 3 kilometers NNW. of the volcano, and the closure of the anomaly has a radius of about 3 kilometers. This anomaly is much larger than any other in the vicinity of the volcano and is not to be accounted for by any topographic effect. It implies that a body of abnormally low magnetism must be located at depth below and somewhat north of the surface expression of the anomaly. It could be a boss of solid rock of low magnetism, such as granite or acid effusives, protruding upward into the generally more magnetic basaltic and andesitic surface mantle. Or it might be the thermal aureole of the Parícutin cupola, the apex of which lies not far below the base of the basaltic and andesitic mantle.

Another reason for showing the Parícutin cupola in an offset position is that such a situation might furnish the explanation for the remarkably continuous and generally steady rate of eruption at the vent during the 9 years of its life. Were a gas-charged cupola tapped at its apex, it seems reasonable to suppose that the consequent eruption would be intense but brief, probably discharging all its pent up pressure in the space of a few months. But were a gas-charged cupola tapped on its flank, as sketched on figure 107, the apex portion of the cupola could continue to act for some time as a reservoir of pressure, the rate of eruption being controlled chiefly by the equilibrium between pressure and the resistance owing to the viscosity. Here the origin of the supposed gas pressure and its possible maintenance at a fairly constant level comes into consideration. There is no doubt, from the inflated character of the majority of the granitic xenoliths, that they originally contained water, whether interstitial or water of constitution of the hydrous minerals, and that it was volatilized and has escaped, either into the enclosing magma during eruption or into the air after eruption. The notably low content of water in the xenoliths after eruption is similar to that of the normal Parícutin lavas (see analyses, tables 2 and 3). The question arises as to whether, at the level of the supposed apex of the cupola, say at 5 or 6 kilometers depth, this inflation of xenoliths and expulsion of volatiles could have been sufficient to produce a build-up of pressure in the cupola. Certainly the tendency would exist, for the granitic (and tuffaceous) material must have contained more water originally than it could hold after being heated to the temperature of the magma, and the pressure build-up could have taken place over a long period of time prior to

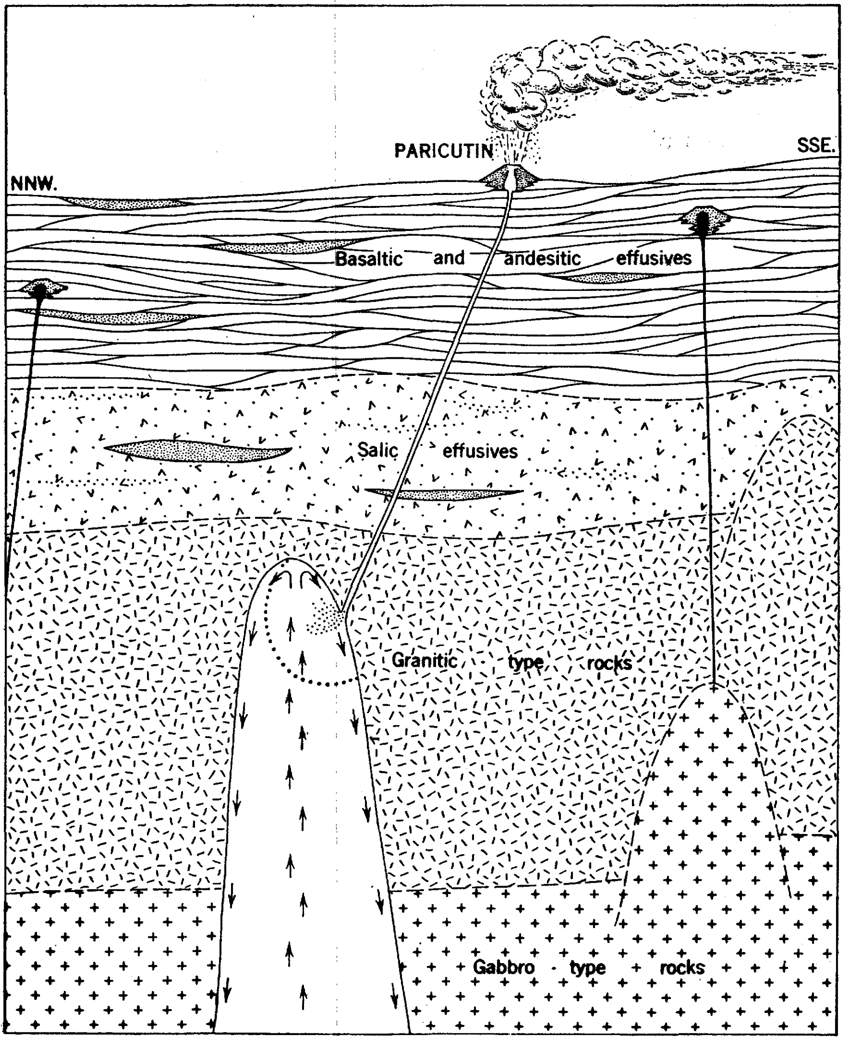


FIGURE 107.—Schematic cross section of Parícutin volcano and its supposed magma cupola. Arrows represent character of slow thermal convection. Area within dotted line represents cross section of approximate volume of magma erupted during 1943–52. Depth of top of gabbroic-type rocks assumed to be about 12–15 kilometers.

outbreak. The surge of especially strong activity from July 1951 until final cessation in March 1952 (Fries and Gutiérrez, 1952a and 1954), would be explainable as flushing of the upper part of the magma column with the escape of pent up reservoir gas when the magma surface had been forced down to the level of the offset outlet.

An offset magma cupola may also account for the apparent lack of effects of fluctuations of atmospheric pressure and tidal force on the behavior of the activity. (See History of the Eruption.) Changes in atmospheric pressure are so slight compared to the supposed pressure in the cupola reservoir that they would have little affect on the rate or type of discharge from a cupola outlet located below the upper surface of the magma in the cupola. Likewise, such a special arrangement would be less affected by daily fluctuations in tidal force than, for instance, a laccolithic magma body.

All this does not necessarily suppose that there would have been a strong concentration of solid or partially melted xenolithic material in the upper portion of the cupola. It is only necessary that the volatile material be released from the xenoliths or immediate portions of the wall rock and rise through the magma without complete resolution in the magma before reaching the apex of the cupola. In this connection, however, it seems worthwhile to examine the possible behavior and movement of the xenolithic material. The specific gravity of the xenoliths of granitic composition should be less than that of the magma especially after having been heated to the magma temperature and perhaps partially inflated. It seems doubtful that even initially there would be any tendency for a xenolith to sink in the magma after its detachment from the wall. Rather there would be a consistent tendency to move upward in relation to the magma; and if the rate of relative upward movement were greater than the rate of the postulated downward convectional current of the peripheral zones of the magma, there would result an absolute upward migration of the xenolith and a tendency to enrich the magma of the upper portion of the cupola in salic material.

A mechanism such as outlined above, while furnishing adequate heat and fitting into the general pattern of the behavior of Parícutin, would seem to leave the chemical and petrographic trends of the successively erupted lavas as a fortuitous relationship. It implies that the chemical differences had already existed in the magma of the cupola, only being arranged in space in such a way that the successively withdrawn samples would show the trend from femic towards salic rock that we now observe in the chronologic series of lavas at the surface. The volume of material actually erupted is such a small fraction of the volume of the supposed cupola (see fig. 107), that, had nonhomogeneities existed in the magma, it would seem just as possible that the sequence of withdrawal could have furnished a series of lavas trending in composition in just the opposite direction, namely, from more salic towards more femic or that the trend of the first few years could be reversed later. This, of course, would be no contradiction of the general progressive development of more salic magma by the combined action of assimilation and crystal fractionation. It only illustrates that the sequence in which the successive portions of the magma were erupted was not necessarily the sequence in which they were initially formed.

The striking random scatter of young cinder cones and associated lavas over the region has been noted and implies that most of the eruptions have been short-lived and that, once interrupted, have seldom been renewed from the same vent. In contrast, the old volcanic pile of Cerros de Tancítaro must have been built up by eruptions from closely spaced vents, some of which were repeatedly active. The transition may be represented by the smaller volcanic piles of the Cerros de San Marcos, Aguila, Angahuan and Los Hornos (see Williams, 1950, pl. 8), finally to the scattered short eruptions represented by the young cinder cones. Whether this type of eruption, which has continued intermittently to the present, can be regarded as a final and decadent phase of the grand cycle of eruptivity from the Michoacán magmas is, of course, a matter of conjecture.

In conclusion, it is of interest to speculate on the possible future activity of Parícutin, admitting the risk involved in predicting the behavior of any volcano. On the basis of the inferred behavoir of the other young volcanoes of the area, it would seem improbable that significant renewal of activity would take place from the Parícutin vent. If the presumption of an offset outlet from the Parícutin magma cupola is well founded, renewal of activity at the Parícutin vent would seem even more improbable, although this does not rule out the possibility of future outbreaks in the area above the cupola apex.

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