Geologic Investigations in the Parícutin Area Mexico

GEOLOGICAL SURVEY BULLETIN 965

Prepared in cooperation with the Secretaría de la Economía Nacional de México, Dirección de Minas y Petróleo, and the Universidad Nacional Autónoma de México, Instituto de Geología, under the auspices of the International Cooperation Administration, Department of State.

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1956

UNITED STATES DEPARTMENT OF THE INTERIOR

Douglas McKay, *Secretary*

GEOLOGICAL SURVEY

W. E. Wrather, *Director*

CONTENTS

[The letters in parentheses preceding the titles are those used to designate the separate chapters]

UNITED STATES DEPARTMENT OF THE INTERIOR

Oscar L. Chapman, *Secretary*

GEOLOGICAL SURVEY

W. E. Wrather, *Director*

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C. - Price $1.00 (paper cover)

CONTENTS

ILLUSTRATIONS

TABLES

GEOLOGIC INVESTIGATIONS IN THE PARICUTIN AREA, MEXICO

EROSION STUDIES AT PARICUTIN, STATE OF MICHOACAN, MEXICO

By Kenneth Segerstrom

ABSTRACT

Parícutin is 320 kilometers west of Mexico City and is reached by air, rail, or paved highway to Uruapan, Michoacán, and thence by 37 kilometers of paved and dirt road to lava-destroyed San Juan Parangaricutiro, 5 kilometers north of the cone.

The volcano is near the southwest edge of the Central Plateau of Mexico, which is largely covered by extrusive rocks and is crossed by an east-southeasterly belt of high volcanoes. The area near Parícutin is characterized by hundreds of young basaltic cinder cones and lava flows. A maximum eroding force per millimeter of precipitation is provided by the concentration of rainfall in brief, high-intensity storms during summer and autumn afternoons. During the winter and spring the surface of the ash is so dry that the wind, usually from the west at that time of year, raises dust clouds almost daily. Before the eruption, about three-fourths of the area around the volcano was forested, chiefly with pines.

The oldest rocks that crop out in the region consist of gabbro which may be similar in age to the quartz monzonite inclusions found in some of the Parícutin ejecta. Interbedded layers of tuff and lava, probably of Tertiary age, overlie this and are in turn overlain by Pliocene and Pleistocene volcanics which form the high Cerros de Tancítaro, a large, maturely dissected volcano whose base is concealed by numerous basaltic cones of more recent age and lava flows in various stages of dissection.

Parícutin erupted from a nearly flat field not far above the base of the long north slope of Cerros de Tancítaro on February 20, 1943. Within a year it had built a cone 336 meters high, although this height was increased by only 24 meters during the following 3 years. Successive flows of lava from Parícutin, composed of basaltic andesite and very blocky in nature, had by 1947 covered an area of about 14 square kilometers and attained a maximum thickness of 150 meters. Thousands of square kilometers of the surrounding terrain have been mantled with pyroclastics, mostly during the first year, in fragments ranging from fine ash to pieces several centimeters in diameter. Varying intensities of eruption, sorting during free descent of ash through the air, raindrop impact, and winnowing by wind have combined to produce a pronounced bedding in the pyroclastics.

The ash mantle is even more permeable than the underlying soil, which itself is highly permeable. However, fine-grained crust forms on the ash where erosion by water or wind is effective, and in places the surface attains such a degree of impermeability that escaping moist air trapped beneath raises bubble mounds.

Ash is eroded, transported, and redeposited by mass movement, water, and—less important—wind. Mass movement is evidenced by tilted forests, illustrating ground creep, and by landslides, mudflows, stream-bank cave-ins, and faulting due to lava movement. Water erosion proceeds from the splashing of raindrops to sheet flow, thence to rill and channel flow. An erosion cycle may be considered as occurring in the mantle itself, with stages ranging from the initial surface of aerially deposited ash to the final, stripped surface of the underlying soil. The rate of channel cutting in the easily removed ash may be very rapid.

Most of the streams in the area are intermittent and are tributary to the westward-flowing Río de Itzícuaro. Storms frequently swell them into dense, sediment-laden floods; then, as the flood velocity decreases, the sediment is redeposited in alluvial fans and on channel floors, on flood plains, and as sheet deposits. Sediment is redeposited, also, from standing water in crater lakes or in bodies of water impounded by lava flows or alluvial fans.

The ash mantle is being gradually removed by landsliding, raindrop splash and sheet erosion combined, channel erosion, and deflation. Moreover, the erosion of some preexisting land forms has been accelerated as a result of the increased cutting power provided by the pyroclastic material carried in the streams.

The change in ground-water flow since the eruption has resulted in marked increases and decreases in the flow of springs, depending on the effect of earthquakes, silting, water supply from lava-trapped drainage, and changes in the water-table level and rate of evaporation.

Recent ash mantles on the volcanoes Jorullo and Ceboruco have been subjected during periods of known length to processes of erosion like those at Parícutin. Their rates of dissection have been largely determined by the particle size of the ash. Vegetation has reclaimed most of these slightly older mantles.

INTRODUCTION

LOCATION AND ACCESSIBILITY

Parícutin lies 320 kilometers due west of Mexico City in the western part of the State of Michoacán. Its latitude is 19°29′33″ N.; its longitude, 102°14′59″ W. (fig. 1).

Uruapan, a semitropical town of 36,000 inhabitants, is approximately 25 kilometers east of the volcano at an altitude of 1,600 meters. It is reached from Mexico City in about 9 hours by following the Guadalajara highway westward to Carapan, where, at kilometer 430, a paved branch road 74 kilometers long leads south to Uruapan. A short line of the Ferrocarriles Nacionales de México provides access to Uruapan, but the rail trip from the capital is longer than that by road, requiring about 14 hours in all. Triweekly flights of the Panini Air Service make the trip from Mexico City to Uruapan in 2 hours. Just north of kilometer 60 on the Carapan-Uruapan highway, or 14 kilometers from Uruapan, a gravel road branches west and leads 23 kilometers to the San Juan encampment, which is 5 kilometers north of the volcano. This dirt road is poorly maintained, and many of its 35 bridges have no planking between the wheel tracks. The drive from Uruapan to the encampment, a place known locally as Cuezeño

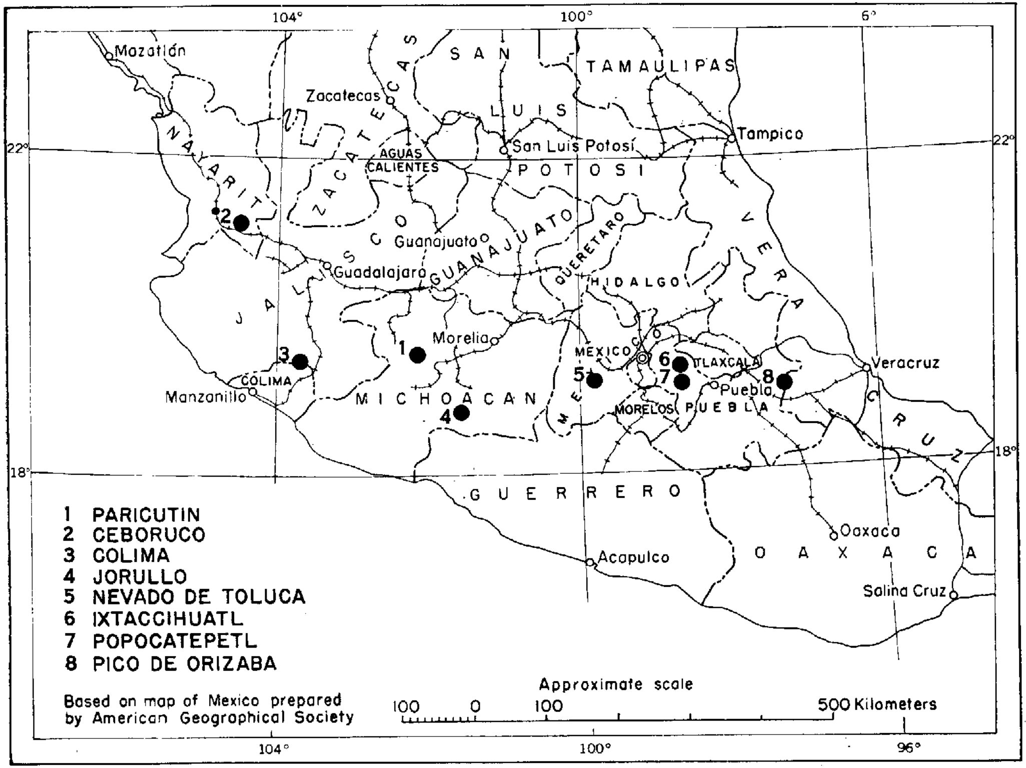


FIGURE 1.—Index map of southern Mexico, showing location of principal volcanoes.

and situated about 1 kilometer north of San Juan Parangaricutiro, requires about an hour and a quarter.

The road from Uruapan to the volcano continues on to Los Reyes, about 30 kilometers farther west, but it is impassable during the rainy season and passable only with difficulty during the dry season. Los Reyes, with 4,000 inhabitants, is approximately 1,300 meters above sea level and is the terminus of another branch line of the Ferrocarriles Nacionales. In spite of the poor condition of the unimproved roads that lead to Los Reyes, there is bus service during the dry season from Uruapan and from Zamora (on the Mexico City-Guadalajara highway).

PREVIOUS INVESTIGATIONS

Most of the previous investigations carried on at Parícutin have consisted of observations of the eruption and closely related phenomena.

The most indefatigable observer has been Celedonio Gutiérrez, whose childhood home is buried beneath the San Juan lava flow and who has since the beginning of the eruption kept a daily written record, only a small part of which has been published.[1] Of the nonlocal observers, Ezequiel Ordóñez has made the greatest number of visits to the volcano and has described its activity most completely.[2] W. F. Foshag was a frequent visitor during the years 1943–45 and has published brief descriptions of fumarolic gases and sublimates.[3] A carefully documented account of the birth of the volcano has been published by Jenaro González R. and Foshag.[4]

Members of the Mexican Instituto de Geología, under the direction of Teodoro Flores, kept close watch on Parícutin in 1943 and have published their observations.[5] Later observations were made for the Instituto by Adán Pérez Peña.[6] During 1944 and 1945, F. M. Bullard [7] made a brief study under a personal grant from the Geologi-

[1] Segerstrom, Kenneth, and Gutiérrez, Celedonio, Activity of Parícutin volcano from May 4 to September 18, 1946: Am. Geophys. Union Trans., vol. 28, pp. 559–566, 1947; Wilcox, R. E., and Gutiérrez, Celedonio, Activity of Parícutin volcano from April 1 to July 31, 1948: Am. Geophys. Union Trans., vol. 29, pp. 877–881, 1948.

[2] Ordóñez, Ezequiel, El volcán de Parícutin, pp. 1–138, México, D. F., Comisión Impulsora y Coordinadora de la Investigación Científica, 1945; El volcán de Parícutin, pp. 1–181, Mixcoac, D. F., Editorial Fantasía, 1947.

[3] Foshag, W. F., Las fumarolas del Parícutin, in Flores, Teodoro, and others, El Parícutin, Estado de Michoacán, pp. 95–100, México, D. F., Instituto de Geología, 1945; Foshag, W. F., and Henderson, E. P., Primary sublimates at Parícutin volcano: Am. Geophys. Union Trans., vol. 27, pp. 685–686, 1946.

[4] González R., Jenaro, and Foshag, W. F., The birth of Parícutin: Smithsonian Inst. Ann. Rept. for 1946, pp. 223–234, 1947.

[5] Flores, Teodoro, and others, El Parícutin, Estado de Michoacán, pp. 1–165, México, D. F., Instituto de Geología, 1945.

[6] Pérez Peña, Adán, Informe sobre el volcán de Parícutin: Bol. minas y petróleo, vol. 16, no. 10, pp. 3–13, October 1946.

[7] Bullard, F. M., Studies on Parícutin volcano, Michoacán, Mexico: Geol. Soc. America Bull., vol. 58, pp. 433–449, 1947.

cal Society of America. Howel Williams, Konrad Krauskopf, G. C. Kennedy, Kenneth Segerstrom, and R. E. Wilcox, all of the United States Geological Survey, have since shared, with Celedonio Gutiérrez and several members of the Instituto de Geología, the task of observing the eruption and have published several papers.[8] The work leading to the present report was part of a larger cooperative program carried on by the Geological Survey and the Instituto de Geología and sponsored by the Interdepartmental Committee on Scientific and Cultural Cooperation, under the auspices of the United States Department of State, and by the Comisión Impulsora y Coordinadora de la Investigación Científica.

Howel Williams [9] mapped a large area around the volcano geologically in 1944 and 1945 and made further investigations at Parícutin in 1947. Konrad Krauskopf has described the mechanism of eruption and lava movement based on observations in 1945 and 1946.[10]

The results of geophysical work carried on in the vicinity of Parícutin by the United States Coast and Geodetic Survey have been described by R. R. Bodle and N. C. Steenland [11] and by Fred Keller, Jr.[12] Frederick Romberg and V. E. Barnes, through a grant from the Geological Society of America, have done other geophysical work.[13] Manuel Medina Peralta, of the Dirección de Geografía, Meteorología e Hidrología of the Secretaría de Agricultura y Fomento, has described most of the geodetic and topographic work done at the volcano both by Mexicans and by Americans.[14]

In 1946 there appeared a preliminary edition (scale, 1:10,000; contour interval, 5 meters) of a topographic map of the volcano area compiled from aerial photographs by stereoplanigraphic methods by the

[8] Krauskopf, Konrad, and Williams, Howel, The activity of Parícutin during its third year: Am. Geophys. Union Trans., vol. 27, pp. 406–410, 1946; Kennedy, G. C., Activity of Parícutin volcano from April 12 to May 3, 1946: Am. Geophys. Union Trans., vol. 27, pp. 410–411, 1946; Segerstrom, Kenneth, and Gutiérrez, Celedonio, op. cit.; Wilcox, R. E., Activity of Parícutin volcano from September 18 to November 30, 1946: Am. Geophys. Union Trans., vol. 28, pp. 567–572, 1947; Wilcox, R. E., Activity of Parícutin volcano from December 1, 1946, to March 31, 1947: Am. Geophys. Union Trans., vol. 28, pp. 725–731, 1947; Wilcox, R. E., Activity of Parícutin volcano from April 1 to July 31, 1947: Am. Geophys. Union Trans., vol. 29, pp. 69–74, 1948; Wilcox, R. E., and Shoup Oropeza, Samuel, Activity of Parícutin volcano from August 1 to November 30, 1947: Am. Geophys. Union Trans., vol. 29, pp. 74–79, 1948; Wilcox, R. E., Activity of Parícutin volcano from December 1, 1947, to March 31, 1948: Am. Geophys. Union Trans., vol. 29, pp. 355–360, 1948; Wilcox, R. E., and Gutiérrez, Celedonio, op. cit.

[9] Williams, Howel, Geologic setting of Parícutin volcano: Am. Geophys. Union Trans., vol. 26, pp. 255–256, 1945; Volcanoes of the Parícutin region: U. S. Geol. Survey Bull. 965–B (in preparation).

[10] Krauskopf, Konrad, Mechanism of eruption at Parícutin volcano, Mexico: Geol. Soc. America Bull., vol. 59, pp. 711–732, 1948; Lava movement at Parícutin volcano, Mexico: Geol. Soc. America Bull., vol. 59, pp. 1267–1283, 1948.

[11] Bodle, R. R., and Steenland, N. C., Report on magnetic survey and seismological observations made in the vicinity of Parícutin volcano, State of Michoacán, Mexico, pp. 1–33, Washington, D. C., U. S. Coast and Geodetic Survey, 1944.

[12] Keller, Fred, Jr., The magnetic work of the United States Coast and Geodetic Survey at Parícutin volcano, Michoacán, Mexico, 1945: Am. Geophys. Union Trans., vol. 27, pp. 350–363, 1946.

[13] Barnes, V. E., and Romberg, Frederick, Observations of relative gravity at Parícutin volcano: Geol. Soc. America Bull., vol. 59, pp. 1019–1026, 1948.

[14] Medina Peralta, Manuel, Trabajos geográficos en los alrededores del Parícutin: Comisión Impulsora y Coordinadora de la Investigación Científica, Anuario de 1945, pp. 245–256, 1946.

United States Geological Survey. Biological studies were made by W. A. Eggler[15] under a grant of the American Philosophical Society and by Norman Hartweg and W. H. Burt, both of the University of Michigan, who have yet to publish their findings. Under a Princeton University grant, Erling Dorf[16] studied the preservation of plants in the area. O. H. Gish, of the Department of Terrestrial Magnetism, Carnegie Institution, and A. P. Eliot,[17] under a partial Geological Society of America grant, made observations on meteorological phenomena, and, under a grant from the Carnegie Geophysical Laboratory, E. G. Zies[18] studied lava temperatures. Arrangements for most of the foregoing studies were made through the Mexican and United States committees for the study of Parícutin. The former is under the Comisión Impulsora y Coordinadora de la Investigación Científica and the latter under the National Research Council. The Geological Society of America grants were made through Richard E. Fuller, chairman of the United States committee.

The studies of Pedro Arias Portillo on the devastation caused by the volcano and those of W. C. Lowdermilk on erosional phenomena associated with the eruption are closely related to the present studies. Arias Portillo, of the Dirección Forestal y de Caza, spent several weeks in 1944 making detailed measurements of damage done to the forest by the lava and ash from Parícutin; his report[19] includes information on agricultural and industrial losses as well as data on hydrology. During August 1945, under a grant from the Geological Society of America, W. C. Lowdermilk, of the United States Soil Conservation Service, with R. W. Bailey, of the United States Forest Service, and Ingenieros José Navarro y Samano and David Llerena Lanzagorta, of the Mexican Departamento de Conservación de Suelos, ran transects, visited the Los Reyes flood plain, made observations at sites where mass movement, rilling, channeling, and flood flows were encountered, and collected samples of ash and underlying soil. The preliminary report on the results of their studies was published in 1947.[20]

---

[15] Eggler, W. A., Parícutin, 1945: Mazama, vol. 27, no. 13, pp. 80–84, December 1945.

[16] Dorf, Erling, Observations on the preservation of plants in the Parícutin area: Am. Geophys. Union Trans., vol. 26, pp. 257–260, 1945.

[17] Eliot, A. P., El volcán de Parícutin: U. S. Dept. of State, Interdepartmental Comm. on Scientific and Cultural Cooperation, Rec., vol. 11, no. 6, pp. 1–5, 1946.

[18] Zies, E. G., Temperature measurements at Parícutin volcano: Am. Geophys. Union Trans., vol. 27, pp. 178–180, 1946.

[19] Arias Portillo, Pedro, La región devastada por el volcán de Parícutin: mimeographed thesis, Escuela Nacional de Agricultura, pp. 1–68, Chapingo, Mexico, 1945.

[20] Lowdermilk, W. C., Erosional phenomena associated with volcanic eruption of Parícutin, Mexico: Am. Geophys. Union Trans., vol. 28, pp. 269–270, 1947.

PURPOSE OF PRESENT INVESTIGATION AND FIELD WORK

The lava and ash from Parícutin, together with the heavy summer rains in the area and the winds of its long dry season, have combined to produce unusually favorable conditions for observing erosional and depositional processes in action. The lava flows have blocked drainage, the ash falls have provided a cover of nearly uniform material to be eroded, and the rain and wind have been active eroding agents. As the terrain has been denuded of vegetation and the ash is unconsolidated, many erosive processes that are ordinarily slow have been accelerated to a degree that permits ready observation.

The purpose of the present investigation has been to study qualitatively, and wherever possible quantitatively, the erosional processes that are taking place in the area. It is hoped that the results, though derived for the most part from the detailed study of only one volcanic area (Jorullo and Ceboruco were briefly visited), can be applied in some degree to an understanding of what happened in areas where earlier eruptions occurred unobserved by man.

Two brief visits to Parícutin during the spring and summer of 1943, the first year of the volcano's activity, and triangulation assignments in its vicinity during the periods January–February 1945 and January–February 1946 provided opportunities to become acquainted with the local physiography. The period July–December 1946 was spent in the field gathering most of the data for the present report, and some additional field work was done in February and March 1947.

Several large-scale topographic maps were made to show the nature of erosion and redeposition in small areas covered by ash, and a small-scale map was made of the flood plain near Los Reyes, where storm waters have deposited much ash on fertile farm lands. Measurements were made of the ash beds and their total thickness, and many samples of the ash were screened to determine the size distribution. Measurements were made of floods, and samples were taken of flood waters. The infiltration rate of water into ash was measured at four places, and at one place the rate was compared with the rate of infiltration into the underlying soil. Sections of preexisting ash and soils were measured and sampled. Slope gradients were measured to determine the limits of the several types of erosion and deposition, and observations were made of blocking and other drainage changes, erosion-cycle stages, denudation and revegetation, agriculture, weather and climate, fresh ash fall, landslides and cave-ins, faulting of ash beds by moving lava, and erosion at Jorullo and Ceboruco volcanoes.

ACKNOWLEDGMENTS

This investigation was first proposed by D. E. White, geologist of the United States Geological Survey, to whom the writer is indebted for many helpful suggestions, particularly about the development of mudflows. W. C. Putnam, of the University of California at Los Angeles, made a special trip to the volcano to help the writer begin the field work and to outline much of the procedure followed later. Little could have been done without Mr. Putnam's valuable suggestions, and the help of the Geological Society of America in providing funds for his trip and—through the United States Parícutin committee—constructing and maintaining a house at the volcano is gratefully acknowledged. The information on preexisting rocks is based almost entirely on the work of Howel Williams [21] and is abstracted in the present paper because it seemed necessary to present a geologic setting for the reader. The writer is also indebted to Mr. Williams for advice on conducting the work. Carl Fries, Jr., in charge of the Geological Survey's program in Mexico, helped in many ways: by supervising the screening of ash samples and the drying and screening of flood samples, by drafting most of the maps, by systematizing the nomenclature of place names, and by procuring supplies needed in the field. Thanks are due R. E. Wilcox, the Survey's observer at the volcano after September 18, 1946, who gave advice on various matters and supplied much of the meteorological information. Mr. White, Mr. Putnam, Mr. Williams, Mr. Fries, and Mr. Wilcox all read the manuscript critically.

R. E. Fuller, as chairman of the United States Committee for the Study of Parícutin Volcano, discussed problems by letter and, during his brief visits to the volcano, verbally. Through the committee, the Geological Society of America financed an aerial survey of the region on April 15 and May 29, 1945, by the Compañía Mexicana Aerofoto. These photographs were used by the Topographic Division of the Geological Survey to test a German stereoplanigraph, the experiment resulting in an accurate topographic map of the region. The military attaché's office of the United States Embassy in Mexico and the Mexican Army's Servicio Geográfico furnished other aerial photographs.

C. S. Ross studied samples from weathered zones below the preexisting surface near the volcano. F. G. Wells gave generously of his time in answering questions, making suggestions, and discussing plans, as did W. D. Johnston, Jr. (who also furnished reference material), W. W. Rubey, Francois Matthes, and I. F. Wilson, all of the Geological Survey; W. C. Lowdermilk, of the United States Soil

---

[21] Williams, Howel, Geologic setting of Parícutin volcano: Am. Geophys. Union Trans., vol. 26, pp. 255–256, 1945; Volcanoes of the Parícutin region: U. S. Geol. Survey Bull. 965–B (in preparation).

Conservation Service; and Konrad Krauskopf, of Stanford University.
Field companions Celedonio Gutiérrez and Jesús and Antonio Saldaña willingly offered their knowledge of the country. Juan Castañeda Díaz, of the Ejidos office in Los Reyes, and Ingenieros José Landrín García and Arnoldo Pfeiffer, of the Compañía Eléctrica Morelia, furnished information regarding floods near Uruapan and Los Reyes. Ingeniero Pfeiffer kindly lent several of his photographs showing flood damage. For the loan of rain gages and thermometers, as well as for meteorological data at Uruapan and Los Reyes, acknowledgment is made to A. P. Eliot, of the United States Weather Bureau, and to the Servicio Meteorológico Mexicano.

REGIONAL SETTING

PHYSIOGRAPHY AND TOPOGRAPHY BEFORE THE ERUPTION

Parícutin is in the southwestern part of the Central Plateau or Mesa Central of Mexico, which forms the highest part of the Republic. The present surface of this physiographic province is composed largely of extrusive rocks, some of them eroded and deposited in valleys and interior-drainage basins as alluvial and lacustrine deposits. Ezequiel Ordóñez [22] describes how these volcanic rocks have buried a mountainous area carved in older sediments and intrusive rocks.

In an east-west belt, about 670 kilometers long, that roughly follows the 19th parallel across the Central Plateau, rise the great volcanoes Pico de Orizaba, Popocatépetl, Ixtaccíhuatl, Nevado de Toluca, Tancítaro, and Colima (fig. 1). Around and between them are many smaller cones, including literally hundreds of young basaltic cinder cones, which, with numerous basaltic and andesitic lava flows, represent the most recent events in the area's long volcanic history.

Parícutin is only one of these recent cinder cones; on an air-photo mosaic of an area approximately 40 kilometers square around the new volcano, some 150 cones can be recognized. The newness of Parícutin, however, distinguishes it from all its brothers. (Jorullo, about 100 kilometers to the southeast, is its most recently active neighbor.) Parícutin's cone lies in an east-trending gap about 15 kilometers wide between two high mountain masses: Cerros de Angahuan (altitude, 3,292 meters) to the north and Cerros de Tancítaro (altitude, 3,842 meters) to the south. The altitude of the lowest part of the gap, location of the now-destroyed town of San Juan Parangaricutiro, is about 2,240 meters. Parícutin broke out 5 kilometers south of this valley, part way up the long northern slope of Cerros de Tancítaro, at an altitude of approximately 2,350 meters.

---

[22] Ordóñez, Ezequiel, Principal physiographic provinces of Mexico: Am. Assoc. Petroleum Geologists Bull., vol. 20, pp. 1291–1294, 1936.

In times past, isolated basins were typical of this region, but the drainage has recently been integrated and is largely tributary to the Río de Itzícuaro on the west or the Río de Cupatitzio on the east. (La Lagunita, before it was covered by lava, was a small undrained basin about 2 kilometers east of the new cone.) The watershed divide that separates the river systems is 6 kilometers east of the volcano (pl.1). Before the Parícutin lava field dammed part of the drainage, most of the area between the two mountain masses drained toward the west into tributaries of the Río de Itzícuaro. Both the Río de Itzícuaro and the Río de Cupatitzio are headwaters of a much larger stream, the Río de Tepalcatepec, which in turn is tributary to the Río de Las Balsas, the largest river in Mexico.

South of the valley of San Juan Parangaricutiro, the maturely dissected slopes of Cerros de Tancítaro, concealed near their base by more recent cones and by flows of basaltic and andesitic material, rise gradually toward a high summit. Northeast of the valley are the more youthfully dissected slopes of Cerros de Anguahan, their base also concealed by recent basaltic cones and flows.

All degrees of dissection may be seen on Parícutin's neighboring cinder cones, of which no less than 35 may be counted on the map in plate 1. The sides of Loma Larga, except below its breached crater, were ungullied before the Parícutin eruption, whereas the flanks of Canicjuata, Corucjuata, and Cuaxândaran are deeply dissected by preexisting barrancas. All the cones except Cutzato and a few others have breached craters, which were probably formed, not by erosion, but by lava movements beneath the cones that caused parts of their flanks to move outward and the corresponding sections of crater rim to slump. Only one of the cones, Cutzato, has an easily recognized satellite cone, but some of the others may have had them too. Their bases, for the most part, probably are deeply buried by lava flows, and observations of Parícutin show that a satellite may well be buried by lava that subsequently issues from the same volcano.

The lava flows result in a cliff-and-bench topography on the long slopes that rise from San Juan Parangaricutiro toward Cerros de Tancítaro on the south and Cerros de Angahuan on the north. The height of the cliffs that rim the benches ranges from 15 to 75 meters; most commonly they are 15 to 20 meters high. The cliffs are not vertical, though steep, in general dipping about 45°. The benches have gentle slopes, usually only 2° or 3°, and their width varies widely between 100 and 1,000 meters. The benches and the bottom of the San Juan Parangaricutiro valley were cultivated fields before the eruption; the cliffs, cinder cones, and upper slopes of Cerros de Tancítaro and Cerros de Angahuan were heavily wooded.

All the main streams in the region have steps and falls where they drop over the sides or fronts of old lava flows. In Barranca de Queréndaro the stream drops a total of 100 meters in two consecutive falls, and vertical drops of 5 to 15 meters are common in all the streams west of Parícutin. In some places the lava stands in high ridges, like the one northwest of Cutzato, where it has a maximum height of about 120 meters.

The long, dissected slopes of Cerros de Tancítaro, however, are not everywhere covered by lava flows and cinder cones. In places the fanglomerates and mudflow deposits that spread from the mountain are exposed. Many of the parallel ridges west of Parícutin are of this nature. Their crests are slightly convex, their average width is about 100 meters, and the barrancas that separate them are as much as 150 meters deep.

CLIMATE AND VEGETATION

Uruapan is the only station near the volcano where meteorological data have been recorded for any length of time, and even there observations were discontinued in 1947. The data recorded at Los Reyes are complete only for the year 1946; those at Peribán give only the rainfall for 1943. At the beginning of July 1946, the writer installed rain gages at Cuezeño, 5 kilometers north of the volcano, and at Jarátiro, less than 2 kilometers north of the volcano. Temperatures were recorded twice a day at Cuezeño, and approximate mean daily temperatures were inferred from these readings. In October 1946, R. E. Wilcox took hourly readings, and on November 9, he began taking daily readings of maximum and minimum temperatures. At Jarátiro no temperatures were recorded.

In tables 1 and 2 the results of precipitation measurements at Cuezeño and Jarátiro for the period from July 1946 through June 1947, together with approximate mean temperatures at Cuezeño, are compared with data supplied by the Servicio Meteorológico Mexicano for Uruapan and Los Reyes.

As shown in table 1, February, March, and April are the driest months of the year in the area, while June, July, August, and September are the wettest. For half the year, from December through May, the rainfall amounts to only 12 or 14 percent of the annual total. During the dry season, periods of 2 to 4 weeks pass between rains, and less than 24 hours after a rain the surface of the ground is usually dry. At the end of May the rainy season begins, and from then until the end of October showers fall nearly every afternoon.

TABLE 1.—*Total monthly precipitation in Parícutin area*

[In millimeters]

Station	Altitude (meters)	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Annual
July 1946–June 1947														
Cuezeño	2,250	288	326	327	217	51	23	67	0	2	2	103	301	[1] 1,707
Jarátiro	2,400	[2] 273	[3] 346	400	217	165	53	78	0	7	-----	168	476	[4] 2,183
Los Reyes	1,300	201	194	152	69	2	0	48	-----	-----	-----	31	182	(5)
Uruapan	1,600	216	333	274	129	10	Trace	49	(6)	(6)	(6)	(6)	(6)	(5)
Mean, July 1931–June 1940														
Uruapan	1,600	389	397	327	153	30	31	22	18	4	4	26	236	1,638

[1] Total for July 1946–June 1947.
[2] Total for 27 days.
[3] Total for 28 days.
[4] Total excludes April and 7 days in July and August.
[5] Data incomplete.
[6] Discontinued.

At Cuezeño from July 1 to October 30, 1946, there were only 8 days without rain and only two occasions when the ground surface was even briefly dry. Practically all this precipitation occurred between 1:00 and 6:00 p. m. in the form of hard local showers, about 90 percent of the rain falling within 30 to 60 minutes. Nearly always the showers fell over small areas, but they were so numerous that the whole volcano area usually received a good daily wetting. Frequently, however, a heavy fall at Jarátiro was not matched by an equally heavy fall at Cuezeño, and vice versa. From July through October 1946 the most intense storms recorded at Cuezeño were the following: July 18, 46 millimeters in 2 hours; July 20, 32 millimeters in 1 hour; August 5, 18 millimeters in 25 minutes; September 12, 40 millimeters in 1 hour; September 16, 27 millimeters in 50 minutes.

The heaviest storms were usually preceded by hail, which whitened the ground at least twice, and heavy electrical discharges accompanied nearly all the storms. "Culebras de agua"—whirlwinds heavily charged with water—occurred several times, and flash floods of brief duration, producing a maximum eroding force per millimeter of precipitation, were an almost daily occurrence. Whether or not there was a heavy storm, fog typically moved up from the west in the late morning and covered Cerros de Tancítaro for most of the afternoon during the wet season.

It is unfortunate that there are no data on precipitation at Cuezeño or some other station near Parícutin for the early years of the eruption. At Uruapan, however, 547.3 millimeters fell during August 1944 and 540.2 millimeters during September 1944. Visitors to the volcano have reported torrential rains for these months, and some of them deduced that these rains were at least partly caused by water from the eruption itself. Certainly enough water originates directly from the eruption, most of the time, to form a cumulus-type cloud over the volcano. During the rainy season this cloud can usually be distinguished down to the crater rim but, with the reduced relative humidity of the dry season, it often does not condense to visibility until it is hundreds of meters above the cone. The daily fogs of the rainy season are visibly augmented by water vapor that condenses above the lava flows. R. E. Wilcox [23] has suggested that repeated vaporization of the rain water by hot lava surrounding Jarátiro may account in part for the precipitation's being heavier at this station than at Cuezeño, which is beyond the limits of the lava. It is unlikely that the small difference in altitude (150 meters) between the two stations accounts for the difference in rainfall.

As shown in table 2, the warmest months of the year in the area are April and May, at the end of the long dry season and immediately preceding the summer rains. Neither the daily nor the seasonal temperature changes are great. During midwinter 2° and 25° C. are the extremes of temperature; usually the daily range is from 4° to 20° C. During the late spring and summer 10° and 35° C. are the extremes; the average daily range is between 13° and 22° C.

TABLE 2.—*Mean monthly temperature in Parícutin area* [1]

[In degrees centigrade]

Station	Altitude (meters)	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Annual
July 1946–June 1947														
Cuezeño [2]	2,250	17	17	16	18	15	13	13	15	17	18	18	17	16
Los Reyes	1,300	24	24	24	22	21	19	18	20	21	24	-----	------	(3)
Mean, July 1931–June 1940														
Uruapan	1,600	20	20	20	20	18	17	17	18	20	21	22	21	19.5

[1] No readings taken at Jarátiro.
[2] Data are approximate.
[3] Data incomplete.

According to Celedonio Gutiérrez, although early-morning frost used to be very common in the region during the winter months, it has not been so heavy since the volcano began to erupt; moreover, water has frozen only rarely, and then lightly, since the beginning of Parícutin's activity, whereas a layer of ice 2 or 3 centimeters thick used to form on still water overnight at San Juan Parangaricutiro. Except possibly

[23] Personal communication.

high on Cerros de Angahuan and Cerros de Tancítaro, the effect of freezing and thawing on erodability is therefore probably inappreciable. One storm each winter may temporarily whiten the top of Cerros de Tancítaro; much more commonly, snow is seen farther to the west on the higher Nevado de Colima. Not even the summer temperatures are warm enough to melt hail very rapidly.

The prevailing upper winds are from the western quadrants during the dry season, April being the month of strongest winds, and from the eastern quadrants during the rainy season. Any variation of upper winds from this pattern is notable. During the summer, or rainy, season surface winds from the west are quite common at Cuezeño in the morning, but they shift in the afternoon. During the winter, and even more during the spring, the surface ash is almost always dry and is easily picked up by the prevailing west wind; the days dawn clear, but by 9 or 10 o'clock in the morning the freshening wind, often with no great velocity, picks up the finest grains of ash and creates a dust storm that lasts until the wind dies down again at 4 or 5 o'clock in the afternoon.

About three-fourths of the area around the volcano, including the hilltops and arroyo bottoms, was forested before the eruption. The forests, which Dorf [24] has described as "an upland, temperate pine-oak association," consisted of approximately 70 percent pine, 15 percent oak, and the rest mainly spruce, madrone, and crab apple. Underbrush was scanty where the forest was dense, but a thick blanket of pine needles retarded erosion. Where the forest was less dense, grasses and shrubs helped greatly to reduce erosion.

The remaining fourth of the area consisted of clearings and low-gradient bottom lands, where the slope of the ground surface was too gentle to permit much erosion by water. Only a small part was actually under cultivation when the eruption began. Fields were plowed by primitive methods, mostly with pointed sticks dragged by oxen, and the crops were corn, wheat, beans, green chile, and some orchard fruits (pears, quinces, apples, peaches, and cherries). The boundaries between the fields were marked by stone fences where the material for their construction was readily available and by ditches where the terrain was not rocky. Both the fences and ditches have been factors in retarding or accelerating erosion, as have the logging roads that were built to exploit the forest resources.

[24] Dorf, Erling, Observations on the preservation of plants in the Parícutin area: Am. Geophys. Union Trans., vol. 26, pp. 257-260, 1945.

GEOLOGY

ROCKS ANTEDATING THE VOLCANO

The rocks predating the volcano have been described briefly by Williams,[25] who states that the oldest rocks he found in the region are of gabbro which may be similar in age to the quartz monzonite occurring as infrequent inclusions in bombs and lava blocks that issue from Parícutin.

The next younger rocks found by Williams consist of nearly horizontal interbedded layers of tuff and lava, probably of Tertiary age, to which he gave the name Zumpinito formation. These rocks are thought to underlie Parícutin at a relatively shallow depth. They are overlain by the Pliocene and Pleistocene volcanics of Tancítaro, which are composed chiefly of lava flows with a minor proportion of interbedded pyroclastic material, and they form the dominant land feature in the region, the high Cerros de Tancítaro. The constructional features of this large volcano have largely been destroyed by erosion; knife-edge ridges and deep canyons are characteristic of its slopes. Cerros de Tancítaro is the source of many of the rock fragments found in the larger streams of the region.

Younger still are the great number of extensive basaltic and andesitic lava flows and small cinder cones like Parícutin, which Williams has shown are arranged for the most part in a random, rather than a linear, fashion. The ash erupted from these volcanoes was deposited in alternate coarse-grained and fine-grained beds of greatly varying thickness. The coarse-grained beds, where observed, are usually thicker than the fine-grained beds.

WEATHERING AND EROSION BEFORE THE ERUPTION

In exposures of the youngest volcanic materials predating Parícutin, the top layer of an ash fall that was subject to weathering for some time before its burial by ash from a later eruption was usually altered to soil. Figure 2 shows a stratigraphic column of preexisting ash exposed in a recent stream cut in a ridge northwest of the Parícutin cone. In a total thickness of 29.45 meters, nine weathered zones of greatly varying thickness may be counted, six of them capped by a brown or ocher soillike layer and two of them including more than one soillike layer. The only fine-grained beds shown are in the weathered zones. Their fineness is probably a product of weathering; with one exception, oxidation appears to have proceeded downward rather than upward from them. Scattered through the coarse-grained beds are many medium-grained beds, generally too ill-defined to be measured or even counted.

[25] Williams, Howel, Geologic setting of Parícutin volcano: Am. Geophys. Union Trans., vol. 26, pp. 255–256, 1945.

DESCRIPTION	THICKNESS (centimeters)
Gray, bedded ash from Parícutin	300
GROUND SURFACE BEFORE ERUPTION OF PARICUTIN	
Ocher soil and fine-grained ash. Sample E-27 is average of top cm.	185
Pale green, coarse-grained, with some black fragments. Weathers rust	100
Yellow green, fine-grained	12
Gray, fine-grained	6
Gray-mottled ocher, very coarse grained	64
Gray, fine- and coarse-grained	22
Gray, mostly very coarse grained but interspersed with 3 or 4 less coarse grained beds each 6 or 7 cm. thick	174
Purplish, slightly less coarse grained	2
Top 4 cm. yellowish, rest grayish; mostly coarse-grained but interspersed with many less coarse beds	142
Probably same as 142-cm. bed but concealed by debris from cliff above. Debris covers bench 5.5 m. wide between cliffs	237
Dark reddish-brown soil horizon (sample E-14) holding up bench	15
Ocher, topped by ½ cm. reddish, fine-grained, compacted	71
Brown, soil-like	2½
Gray, medium-grained	19
Ocher gray, medium coarse grained and fine-grained beds	55
Lens, compacted. Top 6 or 7 cm. brown and clayey, fading downward to ocher and silty. Unbedded and probably water-deposited. Pinches out to northwest	133
Ocher to brown, fine-grained	8
Greenish brown, clay size, compacted	1½
Reddish ocher, medium-grained mixed with fine-grained	37
Yellowish ocher, fine-grained	63
Brown ocher, alternately coarse- and fine-grained	22
Ocher, coarse-grained, gradually fading at 30 cm. down to gray, unweathered. Coarse-grained at bottom	141
Brown, fine-grained, compacted, forming bench	10
Gray, coarse-grained. Contains some less coarse beds each about 5 cm. thick	310
Brown soil-like horizon forming bench	2½
Gray except for flecks of brown ocher in upper 20 to 30 cm., coarse-grained. Contains some medium-grained beds each about 5 cm. thick and some extremely coarse grained beds each 10 to 20 cm. thick	362
Brown ocher, fine-grained, forming strong color contrast with adjacent beds	0.3
Gray, coarse-grained. Some white inclusions	54
Ocher, fine-grained	0.1
Gray, fine-grained. Irregular thickness	1 to 3
Brown soil horizon (sample E-6)	13
Ocher, fine-grained	5
Gray, medium-grained	12
Ocher, very fine grained, unbedded and probably water-deposited	36
Yellow, medium-grained, maximum thickness	120
Varicolored, medium-grained, thin-bedded	14
Light brown, soil-like	3
Greenish ocher, fine-grained, thin-bedded	24
Chocolate, soil-like	2½
Varicolored thin beds, including three brown soil-like horizons	23
Ocher and gray, medium coarse-grained	50
Brown, fine-grained, thin-bedded, compacted	14
Gray, except for mixed ochers in upper 20 to 30 cm. All coarse-grained	375
BOTTOM OF ARROYO	

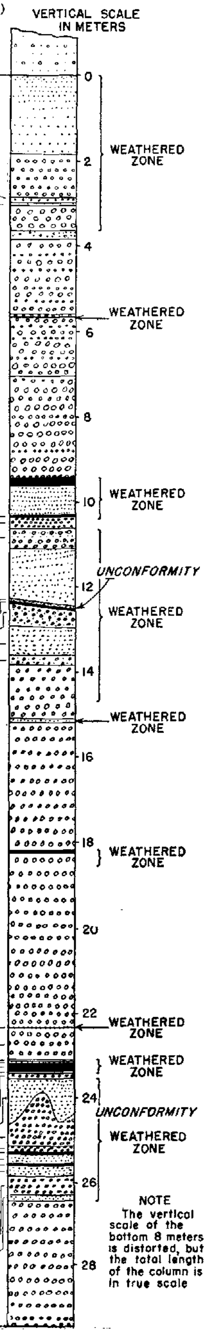


FIGURE 2.—Column of preexisting ash exposed in a stream-cut ridge about 3 kilometers northwest of Parícutin.

C. S. Ross, who examined some of the weathered material, states that a microscopic study indicated much less weathering of most of the material than had been assumed. However, according to Mr. Ross, examination by test tube showed that the glassy fraction of even the least weathered samples had undergone some hydration. The most weathered sample (E–14) contains very thin alteration zones bordering the glass around gas-bubble spaces which are recognizable under the microscope as containing a montmorillonite-type clay, and tiny wisplike areas of the same material have formed within the glass. With it is limonite and, possibly, a kaolin type of material. This determination is confirmed both by differential thermal analysis and by X-ray.

Parts of the 13-centimeter brown-soil horizon (sample E–6), between 23 and 24 meters below the preexisting ground surface, are not essentially different from E–14. The upper zone (sample E–27) appears to be less weathered than that of samples E–14 or E–6. The mineralogy confirms the belief that the three thickest weathered zones, at least, represent real soil zones.[26]

Immediately overlying the two unconformities in the column are zones that probably represent channel fills. In them the material appears to have been derived from the next lower soillike zone and reworked by water. The reworked material is of uniform sorting throughout the maximum thicknesses shown (133 and 36 centimeters), so that bedding is not seen. The 2½-centimeter brown soillike bed just below the 10-meter level may be a bed of weathered material deposited on top of a fresh ash fall by a stream cut headward through the ash into underlying soil. A possibly analogous deposit over ash from Parícutin is described on page 113. Elsewhere through the column, the deposits were probably aerially laid; they show enough particle-size differences between beds to be distinctly layered.

To judge from the great erodability of fine-grained ash from Parícutin, many of the fine-grained beds originally deposited from older cones at the site of the stream-cut ridge must have been removed by erosion. Vegetation probably took hold in the surface layer of coarse-grained, permeable ash, as it did on Jorullo within 90 years after the eruption, and subsequent weathering broke down enough of the coarse particles to form a relatively fine grained soil which was not eroded away because of the already firmly established cover of vegetation.

If any fine-grained, unweathered beds predating the eruption occur near the new volcano, their presence must be explained by one or a combination of the following reasons: (1) They were deposited on

[26] Ross, C. S., personal communication.

relatively flat ground. (2) They were protected from erosion by a cover of vegetation. (3) They were quickly buried by a fall of coarse, permeable ash, by a lava flow, or by water-deposited material, or (4) they were redeposited by water in low or flat areas.

Weathering of the preexisting lavas ranges from practically no visible alteration of flow surfaces to the formation of a surface layer of residual blocks embedded in a clayey matrix.

The Parícutin flows have first filled the low places accessible to them, and flows from earlier volcanoes must likewise have caused an inversion of topography such as that described by C. A. Cotton in which the lava flows "invade and usurp river valleys and become divides." [27] The valleys that are being filled by flows from Parícutin were probably formed, for the most part, by streams following the edges of older lava-filled valleys. Barranca de Queréndaro, 6 kilometers west of Parícutin, is such a stream, lava cropping out for some kilometers on the east side and only tuffs or fanglomerate on the west.

As lava is more resistant to erosion than ash or tuff, the many present streams that cross old flows have cut broad rather than deep channels. For instance, the bed of Arroyo de Huirambosta, 5 kilometers northwest of the volcano, suddenly widens at one place from 10 to 30 meters where it passes from unconsolidated pyroclastic material to flow rocks. In the central part of this broad bed, the stream has carved through solid lava a channel 1.5 meters deep and 2 meters wide, thus producing a box-within-a-box cross section.

ERUPTION OF PARICUTIN

HISTORY AND CHARACTER

The story of Dionisio Pulido and the new volcano that appeared in his "cornfield" on February 20, 1943, has been told repeatedly and in varying form, accounts having been given by González and Foshag.[28] With Celedonio Gutiérrez, the present writer interviewed Pulido on July 21, 1946. The version of the story given at that time, differing in some details from an earlier account by Pulido to Gutiérrez, is substantially as follows:

Earthquakes were felt very frequently during the 18 days preceding the eruption, and on Sunday, February 14, the announcement was made in San Juan Parangaricutiro that it was believed a volcano would erupt on Cerros de Tancítaro. On Saturday, February 20, Pulido went from his home in the village of Parícutin to San Juan Parangaricutiro. A series of strong quakes made him hurry back,

[27] Cotton, C. A., Volcanoes as landscape forms, p. 355, Christchurch, New Zealand, 1944.

[28] González R., Jenaro, and Foshag, W. F., The birth of Parícutin: Smithsonian Inst. Ann. Rept. for 1946, pp. 223–234, 1947.

but following one strong tremor that shook the trees after his return home there was calm. After dinner Pulido left his family again and went to burn branches at Tipúracuaro, a piece of land that he wished later to sow. In Llano de Cuiyúsuru, just below Tipúracuaro and about 2.3 kilometers south-southwest of Parícutin village, he saw a crack in the earth about 5 meters long and 20 centimeters wide. He went on and quickly finished his work. Returning through the Llano, Pulido heard a subterranean roar like that of a mountain torrent. The crack was now about 200 meters long, and vapors were issuing from a short section that was from 3 to 5 meters wide. Alarmed, he walked around the crack and drove his burros, oxen, and mares from a pasture just below Cuiyúsuru. En route to the village he stopped with the animals at a spring that had always had water, but the spring had suddenly gone dry.

According to Dionisio Pulido, the exact spot where the volcano erupted was a small depression, about 1.5 meters deep and 4 meters in diameter, known to the villagers as a place where water always sank into the ground. Unsuccessful attempts had been made to fill it in. On excellent aerial photographs taken by the Compañía Mexicana Aerofoto in 1933, the site as it was 10 years before the eruption can be viewed very realistically through a stereoscope. The pictures show a cleared bench at Cuiyúsuru about 300 by 500 meters in area. Below the bench, a short wooded slope descended steeply to a much larger clearing known as Llano de Quitzocho; above, a similar wooded slope ascended to the bench where Pulido burned his branches.

The volcano was born at 4:30 in the afternoon; by midnight a cone surrounded by burning forest could be seen from Parícutin village. Loud explosions accompanied the eruption of the cone-forming ejecta. Two or three days later the first lava flow—basaltic, viscous, and blocky—was seen issuing from the ground. This flow lasted about 2 weeks, but many others have since issued from vents at the northeast and southwest base of the cone. Much of the explosively erupted ash, lapilli, and bombs that built the cone itself was ejected far beyond the base of the volcano to distances ranging up to more than a kilometer for the bombs and several hundred kilometers for the fine ash, and soon many square kilometers of the surrounding terrain were buried under a mantle of ash. On October 19 a small satellite cinder cone, Sapichu, began to form near the northeast base of the parent cone; its activity continued until January 6, 1944.

Most of the main cone and most of the surrounding ash mantle were deposited during the first year of Parícutin's activity, but successive flows of lava, generally of short duration, have continued with practically unabated strength for more than 4 years. Piling one upon another near the cone, originating now at the northeast, now at the southwest base of the cone, the lava flows had by September 1943 inundated most of Parícutin village and during the period May–August 1944 engulfed the town of San Juan Parangaricutiro. Observatory cabins or casitas built in the Jarátiro area, about 2 kilometers north of the volcano, have been moved four times. By the end of February 1947 even Sapichu, the satellite cone, had been covered. The successive layers of lava have reached their greatest total thickness—probably more than 150 meters—between the volcano and Cerro de Canicjuata.

ECONOMIC ASPECTS

AGRICULTURE

During the first year of the eruption no land was cultivated where the ash was more than 10 centimeters thick, but since then most of the land formerly cultivated and carrying ash thicknesses between 10 and 25 centimeters has again been utilized. Of the area of 233 square kilometers included within the 25-centimeter isopach (pl. 1), about 11 square kilometers, or 5 percent, was actually under cultivation at the time of the eruption. Of this 11 square kilometers, 5 square kilometers has been covered by lava and is therefore lost to cultivation, but about 50 square kilometers of the land covered with 25 centimeters or more of ash is potentially arable in the future, even though most of it was not cultivated at the time of the eruption.

Various attempts were being made in 1946 to reclaim a part of this arable land. In the towns of Zacán and Zirosto, the ash was shoveled off dozens of small plots, and corn, beans, squash, and potatoes were successfully cultivated in the uncovered preexisting soil. On a broad open ridge between Curitzerán and Huanárucua, the land was tilled where the wind had removed most of the ash. Over a large part of the lava-dammed lake bed at Chórotiro, corn was planted in redeposited ash, several meters thick, that contained some preeruption soil; a fine stand sprang up, but floods during July destroyed the crop before the ears matured (fig. 3). On a field near Huanárucua, the ash was fertilized with cow manure and a crop of squash, corn, and beans was harvested, even though there was no admixture of earlier soil. Near Angahuan, where several attempts were made to raise crops in pure ash, the corn sprouted, reached a height of 20 or 30 centimeters, and then turned yellow and died. Some wheat matured, but a small admixture of plant remains may have fertilized the fields. Near Barranca de Tiripan, an effort was made to strip the ash from a large field where the average thickness was 116 centimeters by diverting the flood waters of an arroyo into dozens of hand-excavated furrows on a slight slope; although new and variously located dams were built after each heavy storm, however, the water followed only

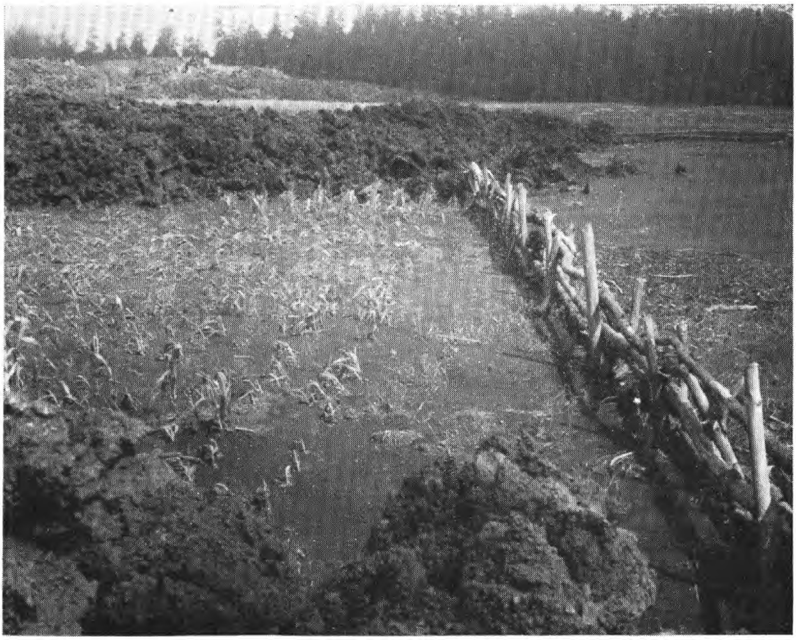


FIGURE 3.—Sowed on March 30, 1946, a cornfield at Chórotiro, near Parícutin, looked like this on August 6.

one furrow at a time, greatly enlarging and deepening it and leaving the others high and dry.

Tractors and bulldozers could push the ash from some of the land in the area, but disposal of the material removed would be a problem where the ash mantle is thick. Indeed, the problem of eventually reclaiming this land for agriculture may be one not so much of stripping as of deposition, since the areas that were cultivated before February 20, 1943, were the flats and the gentle slopes where redeposition by water, rather than erosion, is now taking place. The question is: How much admixture of preeruption soil is necessary for plant growth? Plowing deeper than 25 centimeters in an effort to accomplish admixture of old soil with the ash had not been attempted by 1947.

Damage to the sugarcane fields near Los Reyes by the Parícutin eruption has been threefold: (1) Fields were covered with ash carried down by the great 1943 floods. (2) The floods destroyed the irrigation system by breaking the dams and silting up the canals, and (3) during 1944 a plague of cane-boring insects destroyed most of the crop, another insect that is the natural enemy of this borer having been exterminated by the ash fall.

Inundation of the flood plain near Los Reyes had occurred periodically before 1943, depositing thin beds of reddish or yellowish silt over the cane fields. Thick beds of ash laid down by the 1943 floods were not easily plowed under. According to Juan Castañeda Díaz of the Delegación de Promoción Ejidal at Los Reyes, growers who supplied the two large sugar factories in the district reported 184,000 pesos damage from silting by river-deposited ash for the period January 1943 to May 1944, with 887 hectares affected.

The first large flood in 1943 destroyed all the dams on the Río de Itzícuaro: El Huatarillo, El Aguacate, and Presa de Los Limones. None of the dams built subsequently has lasted more than 5 months; the first or second flood of the season carried away, not only several brush-and-earth diversion dams in 1944 and 1945, but the new 125,000-peso Presa de Los Limones in 1946. The sugarcane fields silted over by ash-laden floods in 1943 lay between El Huatarillo and Los Limones dam sites and along the lower course of the Río de Xundan. The San Juan lava flow of 1944 blocked off half the Río de Itzícuaro watershed, and since then no more cultivated land has been silted over; the floodwaters that destroyed Presa de Los Limones were derived chiefly from the Río de Xundan. More than half the silted land had been returned to cultivation by 1944, but even in 1946 fields were still being reclaimed.

For the period January 1944 to May 1945 growers of the Los Reyes flood plain reported a loss of 80 to 90 percent of the zafra (cut of sugarcane) because of the destruction brought about by the plague of cane-boring insects. A total of 1,263 hectares was affected, and the damage amounted to 746,000 pesos, whereas before 1943 the corn-boring insects destroyed an average of only 5 percent of each cut. Because of the importance of sugar in the Mexican economy, a Presidential decree dated August 20, 1945, allocated 1,425,000 pesos from the public funds to aid the Los Reyes producers. For the next cut the loss was reduced to 15 or 20 percent.

Several different plants had reappeared on the ash near San Juan Parangaricutiro and Zirosto by 1946. A few of the commonest of these were chicolote (white-blossomed prickly poppy), grama (a creeping grass unlike the grama grass found in the western United States), pescadillo (another grass), and carátacua (a bush about 1 meter high).

Fruit growing was important to the local economy before the eruption. The principal fruits in the immediate area were the crab apple, pear, quince, peach, and cherry. The Parícutin pear was famous in this part of Michoacán for its large size and fine flavor. In the part of San Juan Parangaricutiro that was not covered by lava, the unattended orchard trees still bear some fruit, and wild crab apple trees and unattended blackberry bushes bore well near San Juan Parangaricutiro in 1946. Light ash falls over more distant areas caused damage to avocado blooms in 1943 and 1944.

Outside the devastated and semidevastated area within the 25-centimeter isopach (pl. 1), the ash fall has been beneficial to agriculture. In the town of Corupo, where the original ash thickness was 10 centimeters and no crops were harvested in 1943, the corn yield is said to be better now than before. Near Los Reyes the cultivation of some fruits, especially mangoes and guayabas, has been more successful since 1943 than for several years before the eruption, apparently because the falling ash killed a species of destructive fruit fly. Moreover, ash has probably served as a mulch for much of the soil in the region.

About 4,500 head of cattle (mostly work oxen), 550 horses, and some dozens of sheep and goats died as a result of breathing ash from Parícutin. The loss in domestic animals is estimated at 1,000,000 pesos, according to Arias Portillo. Wild animals fled the region in the face of the destructive ash falls of 1943, but since the decline in ash-emitting activity they have been returning—and domestic animals have been brought back—to the devastated zone. The grazing animals browse on deciduous trees such as the crab apple, and hay and silage are brought from outside the area to feed the horses.

Most of the grassland is still ash-covered. Unpublished results of crop experiments made near Parícutin by Eilif Miller, of the Rockefeller Foundation, indicate that one of the difficulties inherent in reestablishing a cover of small plants is breaking the surface of crusted ash.

FORESTS

Forests covering about 75 percent of the area within the 25-centimeter isopach (pl. 1) formerly provided building material and fuel for local use and supplied a thriving turpentine industry as well. Railroad ties, boxwood, shingles, and exotic woods for manufacturing guitars, lacquered bowls, and toys were items of export. Over an area of about 60 square kilometers, or that included within the 1-meter isopach (pl. 1), however, all the trees were killed except a few scattered deciduous trees and even fewer young pines. Outside the 50-centimeter isopach (pl. 1), most of the trees continued to live.

The killing of the forest caused a great revival of the logging industry in an effort to recover the wood before it decomposed. This accelerated rate of cutting has extended deep into the green forest around the devastated zone. During 1946 many thousands of railroad ties were cut (fig. 4); the sawmill at Pantzingo was cutting boxwood from short sections of logs; and everywhere in the forest shingles were being split. Men from Angahuan and particularly from Zirosto, deprived of their livelihood from agriculture, went into the woods to

FIGURE 4.—Hand-hewn railroad ties at Llano de Teruto, near Parícutin.

earn their living, and consequently the forest was damaged far beyond the zone of direct ash damage.

The loss of capital invested in the extraction of pine sap was great. The turpentine cups collected large quantities of ash, which polluted and ruined the sap. Over an area of 8,000 hectares in the region administered by the Dirección Forestal y de Caza, an average of 150 cups per hectare had been installed, and most of this investment was lost as a result of the eruption.

TOWNS AND PEOPLE

The changes brought about in the lives of the people of San Juan Parangaricutiro, Parícutin, Zirosto, Zacán, and Angahuan by the eruption have been profound as the killing of vegetation by ash and lava caused mass migration from the stricken area.

The thousand inhabitants of Parícutin village were forced to leave in April 1943, not only because more than a meter of ash had fallen on their town, but also because a lava flow had reached the outskirts. Land had been purchased for their resettlement at Caltzontzin, 8 kilometers east of Uruapan. The three thousand inhabitants of San Juan Parangaricutiro, most of whom had remained while their fields and houses were buried under half a meter of ash, were forced to abandon their town completely in June 1944 in the face of inundation by lava. Most of these people were resettled in Los Conejos, 5 kilometers west of Uruapan. About half the 1,300 inhabitants of Zirosto were resettled at Sanctuario, but most of them soon drifted back to crowded Los Conejos. Very few of the inhabitants of Angahuan abandoned their homes, but nearly half the people of Zacán moved to Uruapan, Paracho, or Zamora.

A total of 772,000 pesos was donated in 1943 and 1944 by various organizations to buy construction materials, agricultural implements, clothing, medicine, food, and livestock for the people in the devastated area. In 1945 and 1946 other large sums were spent by the Federal Government for building schools and by the Office of Inter-American Affairs for potable-water installations at Caltzontzin and Los Conejos. Hundreds of men from the stricken area, including the famed Dionisio Pulido, from Caltzontzin, and nearly all the able-bodied men of Zacán, went to the United States as agricultural workers or section hands to work under contract for 6 months or more.

An important source of income to the townspeople of Uruapan, Angahuan, and Los Conejos is the tourist industry. Since the first weeks of the eruption thousands of tourists, about equally divided between Mexican and American, have visited the volcano area.

EFFECT ON GROUND-WATER FLOW

The effect of the Parícutin eruption on local ground water appears to have been sevenfold: (1) Some of the old springs have dried up, possibly as a result of earth tremors associated with the eruption. (2) Many of the old springs have been silted up with ash. (3) The lowering of the water table by channel deepening subsequent to the eruption has caused some springs to become dry. (4) The permeability of the ash mantle, by reducing evaporation losses, has made more water available to some springs. (5) A perched water table has been formed above the contact between the permeable ash and the less permeable underlying soil and even to some extent above fine beds within the ash mantle itself. (6) Great volumes of flood water that have percolated into the Parícutin lava field are a potential supply for springs at lower levels. (7) The flood sediments redeposited on the floors of the principal barrancas have in places reduced the surface flow in permanent streams.

1. Since the first day of the eruption, reports of spring failure or at least a marked decrease in spring flow have been frequent, although about half the springs within a radius of 10 kilometers from the volcano have shown no marked change in flow. Arias Portillo reports that a spring called Ojo de Teporícuaro has dried up,[29] and it is said

[29] Arias Portillo, Pedro, op. cit., p. 12.

that some of the springs on the south side of Cerros de Tancítaro have shown such a decrease in flow since 1943 that the spring-supplied public laundry of the village of Tancítaro can no longer be used during the dry season. Celedonio Gutiérrez states that as recently as the period July–August 1946 a large spring at Los Conejos dried up within 6 weeks and has since remained dry. Formerly its large volume had remained nearly constant during periods of both rain and drought. The numerous springs that emerge from beneath a lava flow in Uruapan to form the Río de Cupatitzio have continued the slow decrease in volume first noticed after 1935; in 1946 they were yielding about 87 percent of their earlier volume.

2. Of the springs that were destroyed after the eruption by ash silting, a few have been cleaned out; others, such as the one reported to be at the north base of Cerro de Curupichu, still are buried by ash. Every now and then continued ash fall causes a temporary clogging of the spring-fed pipe lines that supply the towns of Angahuan and Zacán.

3. Before the eruption Ojo de Pomacurán, a well 2 meters in diameter and 1.7 meters deep, was an important source of water in the arroyo just west of the southwest-base triangulation station. It is about 3 meters from the channel of the arroyo, which has been deepened by 0.7 meter since the eruption. Before 1943 the well always contained 10 to 15 centimeters of water, but it has since become dry; apparently the deeper channel has drained the water supply from the well. Seven meters farther downstream, a small seep was seen in the channel floor, but its flow was barely perceptible and the water went underground after running along the stream bed for a few meters.

4. Three of the most important springs of the region, those that supply the Pantzingo sawmill and the towns of Angahuan and Zacán, are at the outlets of old craters. The flow from all these springs has increased somewhat since 1943, apparently because the ash mantle has reduced the loss by evaporation of the water that does not escape as surface runoff. Ojo de Terutsjuata, which supplies Angahuan, is on a shelf in the steep head wall of a barranca that breaches the small crater of Terutsjuata; in contrast to its pre-1943 flow, it more than fills a 2½-inch pipe with water. Ojo de Zacán is similarly located at the outlet of the crater of Cerro de Zacán. Since the mantle of ash from Parícutin covered the area, enough water has flowed at Zacán to keep a 2½-inch pipe filled during winter and summer. Before the eruption the pipe filled to a height of 1 inch during the summer, but for 2 years the spring had dried up completely during the winter.

5. Where new gullies have stripped the Parícutin mantle down

to the resistant surface of the underlying soil, water often trickles out from the ash exposed in the banks. Where the gullies are cut not only through the ash but deeply into the weathered preexisting material, damp zones and seeps occur along the contact. Thus the old surface produces a perched water table. The presence of still higher water tables is indicated by moist and even dripping zones at the contacts between beds of very fine ash overlain by coarse ash.

6. The four strong springs of Sipicha rise in a meadow near the barranca that descends from the lower end of the Parícutin lava field and passes between the towns of Zirosto and Barranca Seca. The combined flow from these springs totals about 8 cubic meters per minute and does not change appreciably with the seasons. It is said that many years ago the volume was about the same, but that for several years before the volcano erupted it was much less. A year after the birth of Parícutin, according to local inhabitants, the volume suddenly increased. It is possible that part of the lava-absorbed flood waters may find their outlet in these springs.

7. Although several streams west of the cone that had been intermittent before the eruption are now permanent, wide fluctuations in the surface flow of several permanent streams have been observed. In September 1946, for example, when it was not carrying flood waters, Barranca de Tiripan was observed to carry about half the volume that it carried in February of the same year. The surface flow, about half a meter wide, was only 5 centimeters deep at the time of the rainy-season observation, yet it had been 10 centimeters deep at the same place when observed during the dry season. Apparently the overloaded floods had meanwhile deposited a permeable bed of sediments on the stream floor, causing much of the subsequent flow to be underground.

In 1946 material from Parícutin had been deposited to a depth of 1 meter at a place on the floor of Arroyo de Huirambosta. There was no surface flow, but water quickly seeped into a pit dug through the redeposited ash and rose within 40 centimeters of the surface, showing that there was strong underflow atop the original preeruption stream bed. At a point 340 meters downstream, where an old lava flow is crossed, the flow of water emerged at the surface. More than a kilometer farther down the same arroyo, redeposited ash and soil in the channel bottom had an elastic quality, and the gelatinlike surface yielded to as much as 10 centimeters of downward thrust before it broke. A sample of this ooze, which was 40 centimeters thick, contained 13 percent water by volume. Eight meters farther on the water flowing under the redeposited surface again emerged to flow in a strong stream across another lava block.

ERUPTIVE PRODUCTS

CINDER CONE

According to Flores and Foshag,[30] the height of the cone above its original base at different times during the first year was as follows: February 23, 1943, 44 meters; February 27, 106 meters; March 30, 140 meters; June 9, 198 meters; and February 20, 1944, 336 meters. In contrast to this rapid early development, the growth has since been very slow.

As seen in plan on vertical aerial photographs taken in February 1946, the nearly circular crater had an outer diameter of about 400 meters, an inner diameter of 200 meters, and an active vent about 40 meters northeast of the center of the inner crater. The apparent base of the cone was elliptical, with a northwest-southeast axis 1,100 meters long and a northeast-southwest axis 950 meters long. The major axis was that of the two high points on the rim, and the minor axis was in line with the northeast subsidiary cone (Sapichu), the explosive vent within the crater, and the southwest lava vents. The crater itself was centered along the short axis about 100 meters southwest of the major axis. Since February 1946, events at the volcano have not greatly affected its dimensions, but the explosive vents within the crater have shifted their position from time to time, with as many as three in existence at once. Two slumps, on the southwest and northeast sides, have formed knolls at the base of the cone; and the piling up of successive flows has appreciably reduced the apparent maximum diameter of the cone. On February 20, 1947, the total height of the cone above its original base was about 360 meters, whereas the height above the lava at its north base was only about 260 meters and, at its south base, 150 meters.

The cone has formed by successive layers of pyroclastic material and has had an outer slope of 31° to 33°. The throat of the explosive vent is composed of coarse agglomerate, which probably occurs only around the eruptive tubes themselves. Within the base of the cone there is undoubtedly some massive lava, which probably does not extend very far up into the cone structure.

The size of the fragments deposited on the sides of the cone varies during different periods of eruption and even on different sides and at different elevations on the cone during the same period, depending partly on the size of the material being ejected, partly on the positions and inclinations of the frequently shifting explosive vents, partly on the distribution of landslides. On October 15, 1946, for example, long narrow landslides or fans of lapilli extended almost from the top

---

[30] Flores, Teodoro, and others, El Parícutin, Estado de Michoacán, plate, p. 152, México, D. F., Instituto de Geología, 1945.

to the bottom of the west slope of the cone. The particles were round and nearly all about 2 centimeters in diameter, although a few scattered scoriaceous fragments up to 10 centimeters across were present. The fans averaged about 4 meters in width, with spaces or grooves between them about 7 centimeters wide and 10 or 15 centimeters deep. The grooves contained many loose, irregularly shaped blocks of scoria averaging 8 centimeters in length, although some were 15 centimeters long.

Farther around the northwest side of the cone, the fans were wider—as much as 5 or 6 meters—with the flat-bottomed spaces between them up to 2 meters wide and 25 centimeters deep. The sorting was even more uniform, and the material making up the fans consisted almost entirely of lapilli 2 centimeters in diameter. The fragments of scoria in these wider grooves were most abundant at the very bottom of the slope. Ten or fifteen meters above the base of the cone, the exposed floors of the grooves were composed of the poorly sorted material with which the cone must have been covered before the landslide fans formed—much fine ash mixed with coarser particles—indicating that the grooves had not formed by a scouring, subtractive process but by the sliding of the newly deposited, well-sorted lapilli. Once formed, however, the grooves had apparently served as passageways for the rolling descent of larger material, as shown by the concentration near the base of bombs and fragments as much as 75 centimeters long but averaging between 20 and 30 centimeters. There was no corresponding concentration of small fragments at the foot of the grooves; instead, the small particles were humped along the volcano's base between the grooves.

On the same day, a large section of the southwest side of the cone had no landslides. There the surface was of unsorted material like that in the floors of the grooves farther west and north. On either side of this section were lapilli fans about 4 to 6 meters wide, but some of the areas between them were as much as three times this width. A broadening of the fans toward the bottom was more noticeable there than on the other sides, and short narrow distributaries branched off from some of the landslides. The fans narrowed almost imperceptibly toward the top of the cone and disappeared just short of the summit. Above their point of disappearance no subtractive grooves could be seen.

Four days later, lapilli fans from 4 to 6 meters wide again appeared on the north side of the cone. The grooves between them were from 1 meter to 3 meters wide and filled with scoria, but the fans did not begin as close to the summit and ended about 30 meters above the base of the cone. Above and below the area of fans, and normal to the slope, were little benches or terraces from 1 meter to 4 meters long and from 5 to 25 centimeters wide on top, composed of scoriaceous fragments. Talus cones of scoria pointing irregular fingers upward from the very base of the cone gave a slight concavity to the bottom 3 to 8 meters of the volcano's profile. The bombs and irregular lava fragments at the base were markedly sorted; the largest pieces, as much as 1 meter in diameter, were thinly scattered and lay farthest beyond the cone, whereas the more numerous medium-sized bombs, up to half a meter across, lay very near the base. The fastest-rolling bombs seen that day descended the whole length of the north slope in 35 seconds.

Arrangements of lapilli fans, scoria terraces, scoria cones, and surfaces of unsorted material on the sides of Parícutin are therefore as changeable as the eruptive activity. Rills and mudflows on the cone are fleeting and uncommon. They are produced when an eruption of fine material is followed immediately by a heavy rain.

Major slumping of parts of the cone's outer flank has occurred at least four times. In June 1943 a section of the north side slumped and rode outward for more than a kilometer on lava injected underneath it. This occurred again in late July and August on a much larger scale, forming the group of fumarole-topped hills later called Las Pirámides. In November 1944 a slump on the southwest side formed a single hill at the base of the cone, and in February 1946 a second slump on the same side pushed the 1944 hill some 100 meters farther out, depositing another hill between the older one and the cone. In January 1947 a slump on the northeast side formed a knoll at the base of the cone near the site of the extinct and nearly lava-buried Sapichu. All four of these mass movements were accompanied by such major lava activity as the opening of a new lava vent.

Less catastrophic mass movements of the flanks commonly accompany the constant tremors that affect the whole cone. Changes are frequent within the crater. During periods of strong eruptive activity when the emission of pyroclastic material is light, it is marked by a series of concentric fissures and fissure faults. The explosive vents in the bottom of the crater change radically from one month to the next in number, appearance, and location, and landslide material that covers up a quiescent vent is not uncommonly blown out again by a resurgence of activity.

LAVA FLOWS

Judging from the mineralogical composition of most of the samples studied, the lava of Parícutin is a basaltic andesite usually blocky and highly vesicular though in small part quite compact. A few of the samples appear to be nearer basalt than andesite. The lava issues from the bocas, or vents, as an incandescent, homogeneous-looking substance, but within a few meters it becomes coated with a nonincandescent crust, which breaks up readily at cascades to expose the still-incandescent material beneath. Rubble falls down the moving front and forms a bed over which the lava advances. There are probably three major factors that influence the size of the blocks: (1) the speed of flow, which is a function of the viscosity and volume of the lava and the cross profile and long profile of the channel; (2) the distance from the vent out of which the lava issues at the surface; and (3) the thickness of solidified crust which is ruptured by plastic flow underneath and by shearing within.[31]

The lavas of Parícutin cannot be mapped separately in detail because of their great number and their complex superposition one over another. Lava streams that appear to have become quiescent often reappear in an active state from a cave far beyond and below the original vent. The largest lava stream, the San Juan flow, started at the southwest base of the cone and followed a circuitous course 10 kilometers long first eastward, then northward, and finally westward. Although it froze over several times and then reappeared from caves en route during its 8 months of activity, it is considered to be a single flow. Most of the flows from Parícutin, however, have continued for only a few weeks or months.

All the lava vents, except that of June 1943, have been at or near the northeast or the southwest base of the cone. Lava emerges from them at a speed of 2 to about 20 meters per minute in a stream from 1 meter to 4 meters wide that gradually broadens manyfold and at its active front slows to a few meters per hour. If the front is dying or extends over a broad area, its speed may be only a few meters per day. The individual flows are usually from 4 to 6 meters thick, but the total thickness of all the superposed flows immediately adjacent to the volcano is from 100 to 150 meters. The area invaded by the lava is about 6 kilometers long by 6 kilometers wide, although the great irregularity of flow boundaries and the presence within this area of one large uncovered tract and several smaller tracts north of the cone reduce the area actually covered by lava to about 22 square kilometers.

In general there is a striking contrast between the south and north borders of Parícutin's lava field. The steep slopes to the south favor the formation of narrow troughs at the edge of the lava, whereas the gentle slopes to the north result in broad lake beds.

In the steeply sloping areas to the south the following cycle of events is repeated: (1) A new lava flow leaves a V-shaped trough between its side and the adjacent hillside. (2) The trough is nearly filled by ash washed down from the hill slope. (3) A new gully forms alongside the lava and cuts through the ash down into the preexisting soil. (4) A succeeding lava flow follows the new gully, fills it to over-

[31] Communicated in part to the author by Howel Williams.

flowing, and, piling higher, forms a new undrained trough between it and the hillside, thus initiating a new cycle. Two factors influence the forming of these lava-side gullies: the permeability of the lava and the gradient of the trough along the lava border.

The borders of the lava flows from Parícutin are still very permeable for the most part. On September 16, 1946, during a violent storm, the writer saw two streams join just before reaching the border of the lava and completely disappear within it. They were each about a meter wide and 10 centimeters deep, and their surface flow was at the rate of 1.7 meters per second. Despite their large volume, they entered the lava without ponding. Moreover, much larger streams were observed to enter the lava after each heavy rain, although not without being briefly impounded. The high permeability of the lava from Parícutin is temporary, however; probably the interstices are gradually being filled by the material suspended in the floods that enter the lava. At the base of Cerro de Nuréndiro, south of the volcano, the decreasing permeability of the lava is so effective in raising the water table that even in the middle of the dry season the marginal ash is boggy at the mouths of the principal gullies.

The gently sloping areas that border the lava field, principally to the north, contain many extensive lake basins. The largest are at Llano Grande, at Chórotiro (where the bottom is about 1,500 meters long and from 50 to 500 meters wide), and just north of Cerro de Curupichu, all at the edge of the San Juan lava flow. When the smaller basins are filled, their watersheds become integrated with the larger basins. During 1945 and 1946, as the smaller ponds to the south began to overflow, most of the drainage east of the cone became tributary to the lake north of Curupichu.

Although still much too permeable to stop the flow of water, the lava may slow it during floods. Ponds of storm water formed at the lava borders never last more than 2 or 3 hours except when the silt deposited in depressions makes surfaces impervious enough to hold shallow bodies of water, which gradually disappear chiefly by evaporation. Such depressions are very narrow, few are more than 100 meters long, and their orientation is roughly parallel to the border of the lava. They are about 15 to 50 meters distant from the lava border, evidently because the bottom of an area of ponding tends to be slightly higher against the lava "filter" than away from it. In places a small sink develops at a point 1 meter or 2 meters out from the very edge of the lava, where water drains through mud cracks and enters the lava field.

Just east of the San Juan lava flow, in the bed of a lake whose drainage had just been integrated with that of a larger lava-blocked basin to the north by means of a new lava-side gully, an unusual pond was formed. Storm water discharged from a side stream was ponded by the alluvial fan that had been formed by the main gully before it broke through the divide to the north. This body of water was crescent-shaped, as a new fan had been built outward into the pond by the same storm discharge.

The arroyo just south of Cuezeño—5 kilometers north of the cone—formed during the 1945 rainy season, became deeper during June and July, and from August on was again being filled by deposition. The San Juan lava flow, into which the flood waters from this arroyo drain, filters out increasing quantities of the material carried in suspension. The filtering process becomes more and more effective as the interstices in the lava are filled, resulting in the silting and raising of the bed at the arroyo's mouth. During August and September 1946 the channel of this arroyo was filled with 70 centimeters of water-deposited sediment.

In 1943 and early in 1944, before the lava flows were very extensive, some ash was removed from the area by streams now blocked by lava. By filling most of the San Juan valley, lava flows from Parícutin have blocked the drainage of about 40 percent (nearly 100 square kilometers) of the terrain that is covered by ash to a depth of more than 25 centimeters. Fifty percent (about 60 square kilometers) of the terrain that is mantled by ash more than 50 centimeters deep is lava-blocked. (These figures include the 22 square kilometers actually covered by lava.) All this area formerly drained into the Río de Itzícuaro, which flows to the west; thus it is unlikely that the Río de Itzícuaro will again inundate Los Reyes as it did in 1943 when practically none of the tributaries in its watershed were blocked.

The greatest extent of lava blocking was completed in March 1946 when the farthest-advanced lava front stopped at Huirambosta, 5 kilometers north-northwest of the volcano. In October 1946 a new barranca, lying along the east base of Cerro de Canicjuata, that would have started draining the Cocjarao-Canicjuata area, just west of the cone, was effectively filled by lava. However, gullies are always being formed alongside the lavas, and occasionally lava-impounded storm waters break over low divides, so that the trend is for more and more of the watershed to be reopened to normal drainage. Early in the 1947 rainy season, flood waters broke over the watershed divide at the south base of Cerro de Canicjuata and reopened a not inconsiderable part of the drainage from the area immediately to the southwest of the cone. (This change is not shown on pl. 1.)

As a result of drainage blocking, the stream channel below the lower end of the San Juan lava flow became less and less deep during 1945. The lava that had filled the watercourse upstream had so effectively cut off all flow from the main stream and its tributaries that the material washed down from the banks could not be carried away by the current. Finally a northern tributary cut a new outlet channel along the lava border, and beyond the end of the lava the new channel spilled its load into the old arroyo, forming a new bed that in September 1946 was cut to a depth of 65 centimeters in water-deposited ash from Parícutin. The lava flow that came to a halt in March 1946 in the same area (Huirambosta) dammed a watercourse similar in size to that invaded by the San Juan flow. The two streams join about 300 meters west of the westernmost lava tongue. The south fork still had nearly all its source water cut off, and through the rest of 1946 was gradually filled with material washed down from its banks. During a few weeks 60 centimeters of new sediment was deposited. Where the two Huirambosta watercourses join to form the Río de Itzícuaro, the channel in the north branch was, in September 1946, 70 centimeters lower than that in the south branch (fig. 5).

FIGURE 5.—Forks of Arroyo de Huirambosta, north-northwest of Paricutin, showing how the north branch (foreground) has deepened its channel below the level of the south branch.

ASH

PHYSICAL PROPERTIES

In common with other products of the eruption, the ash from Parícutin is basaltic andesite. It consists of glass shards, pieces of vesicular and dense lava of lithoidal texture, and crystals of olivine. No marked variation in composition and mineral content of the ash, either regular or erratic, has been observed. Its color ranges from light greenish brown to dark gray or nearly black, the frothy particles generally being lighter-colored than the denser material. Individual particles are irregular in shape and range from fine dust to fragments several centimeters in diameter. Medium-sized particles of ash from Parícutin range from about 0.15 to 0.4 millimeter in diameter. Ash particles of more than 4 millimeters in diameter, called lapilli according to the classification of pyroclastic material set up by Wentworth and Williams,[32] are not uncommon, nor are particles of clay-size fineness (less than 1/256 millimeter).[33] Average samples of ash not reworked by wind or water are poorly sorted; a single sample may contain particles ranging from lapilli down to clay size. The classification of a given sample of pyroclastic material is determined, however, by the size of its predominant particles, and in spite of the presence of lapilli it may still be called ash if the finer particles predominate.

Carl Fries, Jr., determined the specific gravity of the following particle-size fractions of a group of ash-laden flood samples, collected in 1946, which contained small quantities of preeruption material:

Diameter (millimeters):	*Specific gravity*
Less than 0.15	2. 69
0.15 to 0.18	2. 68
0.18 to 0.25	2. 67
0.25 to 0.30	2. 66
0.30 to 0.42	2. 65
0.42 to 0.6	2. 6
0.6 to 1	2. 5
1 to 2	2. 4
Greater than 2	1. 5 to 2. 2

The specific gravity of the coarse particles varies widely, depending on whether the pieces are vesicular or dense. In general, however, the specific gravity drops as the particle size increases, for the large fragments usually contain more vesicles than the small particles at any given place. The fine particles may in greater part be the dense walls of vesicles shattered by the eruptive activity.

DISTRIBUTION, THICKNESS, AND BEDDING

Most of the ash mantle was deposited during the first year of the eruption (1943), at the same time that the greater part of the cone was built. One of the heaviest ash falls occurred from March 19 to April

[32] Wentworth, C. K., and Williams, H., The classification and terminology of the pyroclastic rocks: Nat. Research Council Bull. 89, Rept. of Comm. on Sedimentation, pp. 15–53, 1932.

[33] Wentworth, C. K., A scale of grade and class terms for clastic sediments: Jour. Geology, vol. 30, pp. 377-392, 1922. Wentworth's terms, as used in the present paper, refer only to particle size and have no significance as to origin or mineralogical character of the ash.

17, when the prevailing upper winds, as usual in the dry season, were from the west. Arnoldo Pfeiffer measured the fall on April 9 at Morelia, 125 kilometers east of the volcano, and found it to be 112 grams per square meter for the 24-hour period. On the same day Ariel Hernández Velasco found the 24-hour fall at Mexico City, 320 kilometers east of the volcano, to amount to 136 milligrams per square meter.[34] However, very heavy falls occurred in the opposite quadrant during the entire summer or rainy season of 1943, when the prevailing winds were from the east. The isopach map in plate 1 shows how the curves of equal ash depth are elongated to the east and to the west—particularly to the west because the east winds typical of the rainy season deposited a thicker layer to the west of the volcano than was laid down to the east by the west winds of the dry season. The old cones of the region are sway-backed because of this seasonal change in deposition. R. E. Wilcox [35] has pointed out, however, that the sway-backed profile of the Parícutin cone is due largely to the rafting out of the northeast and southwest flanks and slumping of the rim.

Near San Lorenzo, along the road between the volcano and the Mexico City-Uruapan highway, several road cuts show bedding of old ash. At each place, the convex crests of the beds are west of the present ridges which they underlie. The prevailing west winds of the dry season have caused the ridge crests to migrate eastward, a process now being repeated on the ash from Parícutin as the west sides of exposed ridges are stripped by wind and the material is redeposited on the east sides.

After the first year or two the great decline in Parícutin's eruptive activity made itself felt. At the north foot of Cerro de Canicjuata, 850 meters west-northwest of the volcano, only 3 centimeters of ash fell from October 1945 to July 1946, a period of generally light eruptive activity and variable winds. At the same place, 3 centimeters of new ash were deposited during August 1946, 7 centimeters more to September 18, and 3.5 centimeters from then until October 11. From August 2 to October 11, only 3 millimeters were deposited at Curínguaro, 2 kilometers east-northeast of the cone, indicating the influence not only of wind direction but of distance from the eruptive throat on the distribution of ash. Table 3 shows how rapidly the ash thickness decreases with distance from the cone.

Three factors that are impossible to express quantitatively have a profound influence on the shape of the ash profile in any given direction from the source cone: (1) frequency and intensities of wind in that direction, (2) variation or range of ash size, and (3), in the zone

[34] Hernández Velasco, Ariel, Estudios de las cenizas del volcán caídas en la Ciudad de México, in Flores, Teodoro, and others, El Parícutin, Estado de Michoacán, pp. 141–145, México, D. F., Instituto de Geología, 1945.

[35] Personal communication.

TABLE 3.—*Thickness of ash mantle at various distances west-northwest of Parícutin cone, September 1946*

[Data obtained, except for the figure in parentheses, from pits excavated in the mantle]

Distance from base of cone (meters)	Name of locality	Thickness of ash mantle (centimeters)	Decrease in thickness per 100 meters (centimeters)
110		[1] (3,000)±	256.7
850	Casita Canicjuata	1,100	77.0
1,500		600	50.0
1,700		500	33.3
2,000		400	16.7
2,600	Corucjuata triangulation station	300	10.0
3,600	Near Llano del Pueblo Viejo	200	4.5
5,800	Near Tiripan	100	2.3
8,000	Zirosto	50	1.0
10,500	Barranca Seca	25	

[1] Calculated from the total thickness at Casita Canicjuata (1,100 cm.) by using the empirical ratio of 38 to 14, which is the ratio of the increments at those two points between Aug. 2 and Oct. 15, 1946.

very near the vent, varying positions and inclinations of the most active vents within the crater. Interestingly enough, however, the fall of ash at Cuezeño and near Jarátiro from November 1946 to June 1947, as reported by R. E. Wilcox, was proportional to the total thickness at those two places, indicating some stability in the ash-profile curve in those directions.

The results of ash-thickness measurements made during July, August, and September 1946 are shown in plate 1 (see also fig. 6). A comparison of this map with one prepared by Howel Williams [36] for ash thicknesses to May 1945 shows some increases to the west of the cone but little difference to the east. Measurements were made where the influence of erosion and redeposition was negligible, usually on or near crests of broad ridges.

The measurement at Casita Canicjuata, on the crest of a ridge nearly buried by lava, showed by far the greatest thickness of ash. In August 1946 a pit 516 centimeters deep was dug there, but because of cave-ins the underlying soil was not reached. In September an exceptionally heavy rain caused water to be impounded between the lava and the ridge until it overflowed and, in the one storm, cut a deep gully into the ridge crest (fig. 7). A pit was dug in the bottom of this gully, but cave-ins again discouraged digging at a depth of only 747 centimeters. Subsequent storms had by October 11 deepened the gully until it exposed the prevolcano surface and the thickness of the entire ash mantle could be measured; it amounted to 1,083 centimeters. Finally, on October 18, a new lava flow began cascading through the cut and down the west slope of the ridge, burying the greatest thickness of Parícutin ash mantle thus far exposed (fig. 8).

[36] Williams, Howel, Geologic setting of Parícutin volcano: Am. Geophys. Union Trans., vol. 26, pp. 255–256, 1945.

FIGURE 6.—Pit dug for measurement where mantle of ash from Parícutin was 238 centimeters thick.

With the aid of the isopach map (pl. 1) and a few measurements of ash thickness made beyond the outer (25-centimeter) isopach, the volume of ash from Parícutin was roughly calculated out to the inferred 1-millimeter isopach, which probably passes near Guadalajara, Jalisco. In table 4 the volumes within different isopachs are given separately. The total volume of ash erupted by Parícutin probably amounts to two or three times the volume of lava extruded in the

FIGURE 7.—New barranca eroded into the Casita Canicjuata ridge, near Parícutin, during a single storm.

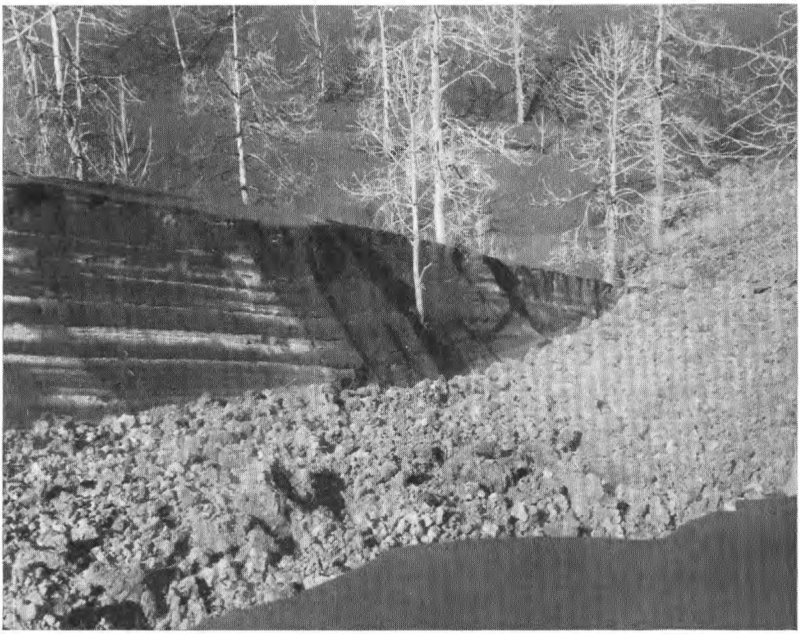


FIGURE 8.—Midslope in the Casa Canicjuata barranca (fig. 7) on the day that a new lava flow started through it.

form of surface flows. The volume of ash and lava together is probably slightly less than 1 cubic kilometer.

TABLE 4.—*Volume of ash erupted by Parícutin, for areas within different isopachs*

Area	Size of area (square kilometers)	Volume of ash (cubic kilometers)[1]	Weight of ash (millions of metric tons)
Parícutin cone	----------	0.125	[2] 300
Within 12-meter isopach	2.7	.16	[3] 400
Within 5-meter isopach	7.5	.20	[3] 500
Within 1-meter isopach	61	.30	[4] 800
Within 50-centimeter isopach	119	.34	[4] 900
Within 25-centimeter isopach	233	.38	[4] 1,000
Within 8-centimeter isopach [5] (Los Reyes)	750	.45	[4] 1,150
Within 1-centimeter isopach [5] (Jiquilpan)	6,000	.60	[4] 1,550
Within 1-millimeter isopach [5] (Guadalajara)	60,000	.65	[4] 1,700

[1] All volumes include that of the cone itself.
[2] Based on specific gravity of 2.4 and stated to nearest 50 million.
[3] Based on specific gravity of 2.5.
[4] Based on specific gravity of 2.6.
[5] Assumed to be confocal to the 25-centimeter isopach.

An inclined slope receives less falling ash per unit of area than a flat area at the same place. The numerical differences are expressed as follows, assuming that the given slopes replace a horizontal area and that the ash is falling vertically:

Slope inclination (degrees):	*Percent ash deposited, relative to same unit of flat area*
0	100
10	98
20	94
30	87
40	77

Thus a slope of 32°, which is common for cinder cones in this region, receives only 85 percent as much ash per unit of area as it would if it were level. If, because of strong winds, the ash were falling at an angle other than vertical, the windward slopes—generally those facing the volcano—would receive a heavier deposit per unit of area than the leeward slopes and perhaps even more than the flat areas.

R. E. Wilcox [37] has pointed out, however, that the apparent thickness measured on a vertical section of an inclined deposit is comparable to the true thickness measured on a vertical section of a horizontal deposit, assuming no creep or other disturbance has occurred.

The size distribution of the ash particles erupted during one period may differ greatly from that of the next period. Combined with the rude sorting that occurs in the air (the fine-grained material from any one explosion falls more slowly) and the partial sorting on the ground that results from raindrop impact and wind winnowing, this variation accounts for a pronounced stratification in the original ash deposits. The beds vary in thickness from less than a millimeter to half a meter, contiguous beds showing differences in grain size that may be greater than the differences in any one bed at varying distances from the cone. Beds of very fine-grained ash are deposited near the cone as well as far from it; however, the coarsest particles—at times carried to great distances—are noticeably larger near the cone than far from it. The ash usually remains where it falls until eroded by wind or water, although rounded lapilli that fall on slopes may roll down into low areas and accumulate as small lenses or fans.

Here follows a description of the 391-centimeter section of ash from Parícutin exposed in a pit at Jarâtiro, about 2 kilometers north of the cone. The beds are listed from top to bottom.

[37] Personal communication.

Description of bed	*Thickness, in centimeters*
Mostly unstratified fine-grained material; sample A–24 taken from finest-grained part	56
Coarse-grained; sample A–23	5.5
Fine-grained	15
Very coarse grained; sample A–22	6.5
Fine-grained	6.5
Coarse-grained	6.5
Very thin beds, alternately fine- and coarse-grained	5
Very coarse grained	10
Fine-grained except for two groups of very thin coarse-grained beds; sample A–21 taken from fine-grained part	53
All coarse-grained; sample A–20	10
All fine-grained	16
Very coarse grained	6
Fine-grained	11
Coarse-grained	5
Fine-grained	3
Coarse-grained	1
Fine-grained	4
Very coarse grained lapilli	4
Fine-grained, including two thin beds of coarse-grained material; sample A–19 taken from coarse-grained part	37
Thin beds as little as half a centimeter thick, alternately fine- and coarse-grained	25
Fine-grained	5
Coarse-grained	3
Fine-grained	5
Mostly coarse-grained, but with two thin layers of fine-grained	16
Fine-grained	11
Mostly coarse-grained, but including three beds about 2 centimeters thick of fine-grained material; sample A–18 taken from coarse-grained part	40
Fine-grained; sample A–17	23
Coarse-grained	2
Preexisting soil.	
Total	391.0

Figure 9 shows graphically the size distribution of the material in the samples taken from this Jarátiro pit, ranging from nearly 90 percent gravel size to more than 25 percent silt-and-clay size.

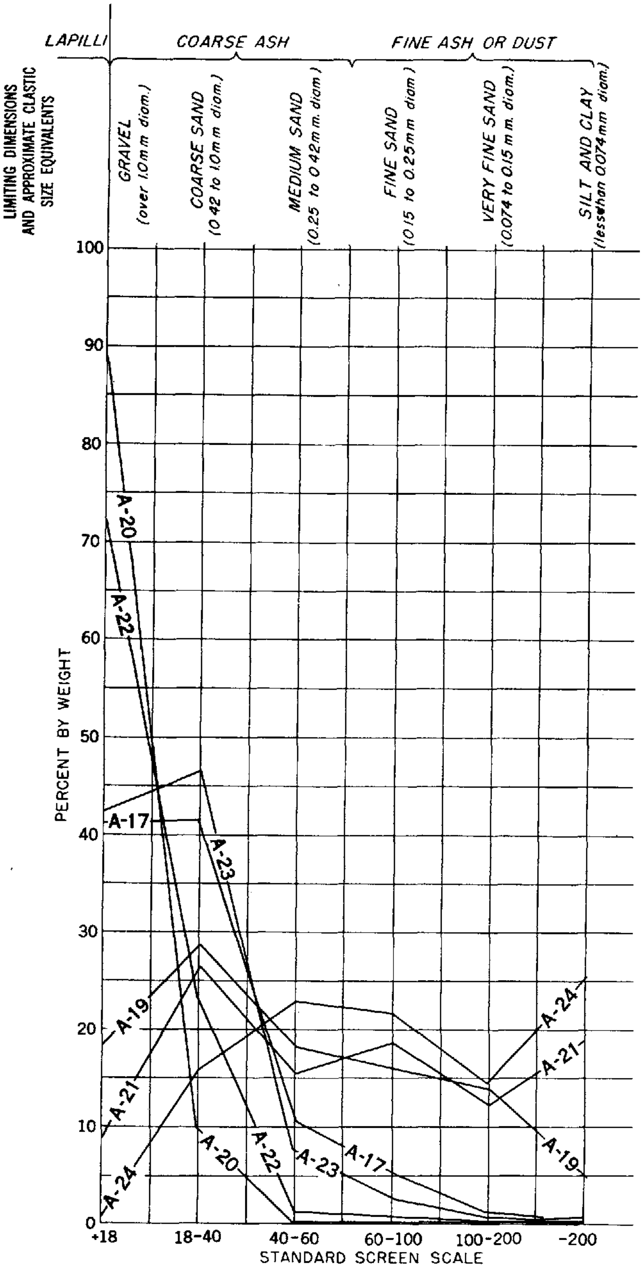


FIGURE 9.—Graph showing size distribution of particles in seven samples of ash from Parícutin taken from a pit at Jarátiro.

The bedding in the ash at Jarâtiro is typical of that encountered throughout the Parícutin mantle. In the top meter of ash on the summit of Cerro de Canicjuata, 17 individual beds or groups of beds ranging from 88 percent gravel size to 42 percent silt-and-clay size were measured. Samples taken from some of these beds—four of them composed of a total of 40 thin layers of alternately coarse and fine material—were screened and are described graphically in figure 10. Beds were difficult to correlate from one measurement site to another, but two marker beds were found that could be recognized in several pits. These are described in table 5.

TABLE 5.—*Marker beds in mantle of ash from Parícutin at four localities northwest of the volcano*

[All measurements in centimeters]

Locality	Total thickness of ash mantle	Depth to very fine grained marker bed	Thickness of this marker bed	Depth to very coarse grained marker bed	Thickness of this marker bed
Tiripan	104.0	9.0	0.5	40.5	1.0
Cuaxândaran	158.0	15.5	2.5	66.5	2.0
Sinâmichu	170.0	15.0	4.0	67.0	2.3
Corucjuata	297.0	23.5	2.5	106.0	5.5

Outward from the cone the proportion of gravel size in the coarsest-grained beds drops, as shown in table 6, compiled from the data in figures 9, 10, and 11, but there is no corresponding increase in the proportion of silt-and-clay size in the finest-grained beds.

TABLE 6.—*Proportions of gravel size, sand size, and silt-and-clay size in ash from Parícutin at six localities*

Locality	Distance and direction from cone	Coarsest-grained bed		Finest-grained bed	
		Percent gravel size	Percent coarse-sand size	Percent fine-sand size	Percent silt-and-clay size
Jarâtiro (fig. 9)	1.5 km. to the north	89	10	15	25
Canicjuata crater (fig. 10)	1.5 km. to the west	86	11	10	43
Llanos de La Caja (fig. 11)	3 km. to the southwest	51	36	27	12
Lava ridge south of Llanos de La Caja (fig. 11).	4 km. to the southwest	22	56	13	22
Cuaxândaran	5 km. to the west	12	59	26	34
Saddle south of Peña del Horno	8 km. to the southwest			22	29

Also, the proportion of medium- and fine-sand-size particles in the coarsest-grained beds becomes higher, although the proportion of medium- and fine-sand-size grains in the finest-grained beds remains about the same (table 7). With greater distance from the cone, therefore, the contrast between the beds in any given section becomes less. Moreover, the average thickness decreases.

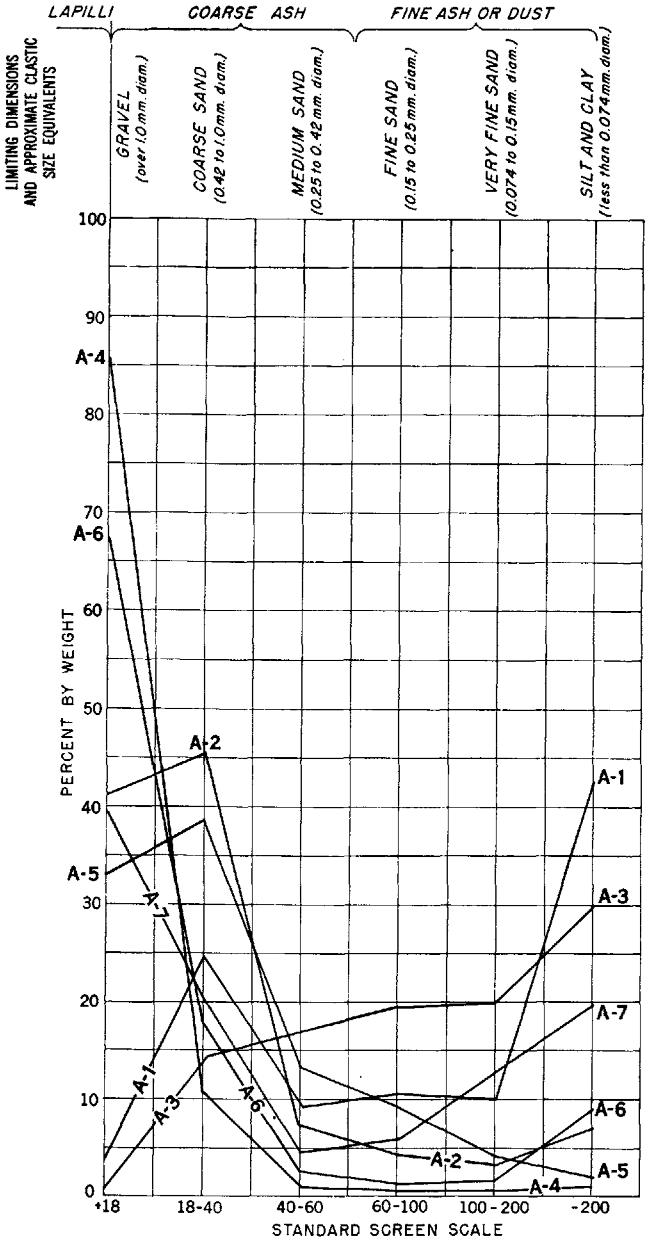


FIGURE 10.—Graph showing size distribution of particles in samples of ash from Parícutin taken from a pit on top of Cerro de Canicjuata.

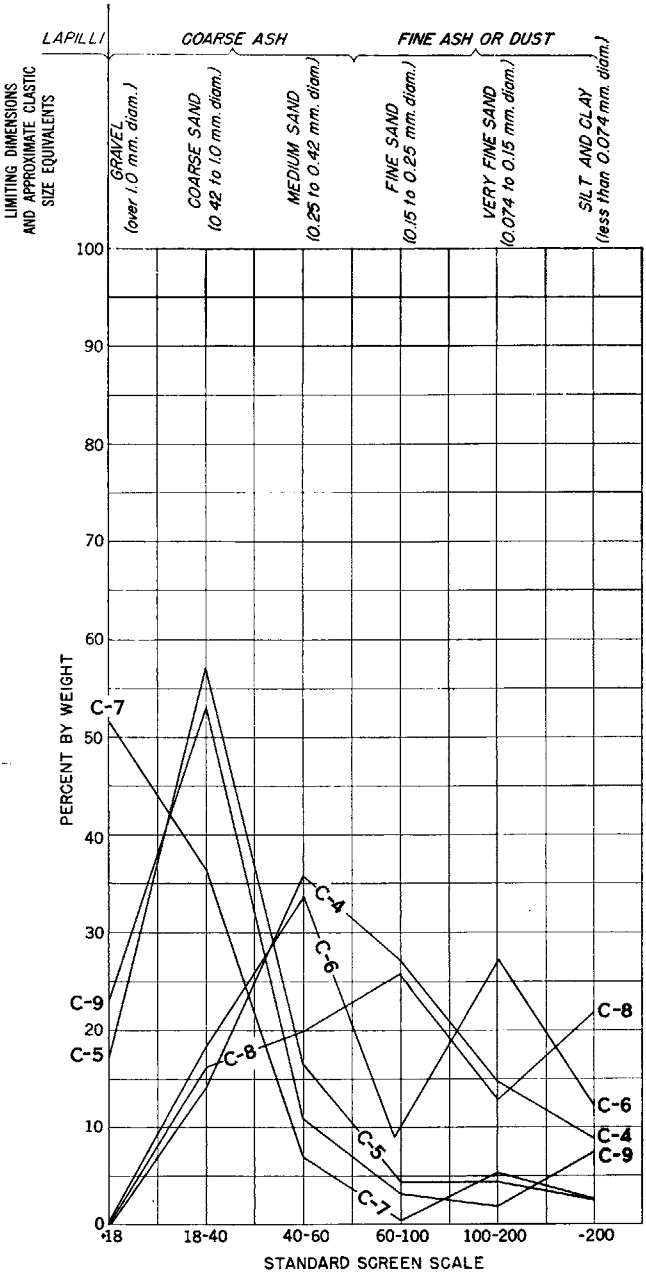


FIGURE 11.—Graph showing size distribution of particles in ash samples taken from various places southwest of the Parícutin cone.

TABLE 7.—*Particle sizes in coarsest- and finest-grained beds of ash from Parícutin at five localities*

Locality	Distance and direction from cone	Percent medium- and fine-sand-size particles (0.15 to 0.42 millimeter in diameter)	
		Coarsest-grained bed	Finest-grained bed
Jarátiro (fig. 9)	1.5 km. to the north	(1)	45
Canicjuata crater (fig. 10)	1.5 km. to the west	1	37
Llanos de La Caja (fig. 11)	3 km. to the southwest	8	42
Lava ridge south of Llanos de La Caja (fig. 11)	4 km. to the southwest	14	45
Cuaxándaran	5 km. to the west	25	40

[1] Less than 1.

The total number of beds deposited varies considerably from place to place, depending on the distance and direction from the cone. Frequent great changes in particle size, such as apparently occur near the cone, are to be expected ordinarily, but different eruptions do not necessarily emit alternately coarse-grained and fine-grained material; there are successive periods of eruptive activity so nearly alike that the ash beds deposited cannot be easily distinguished one from another, as in the top 58 centimeters at Jarátiro.

Figure 12 shows the size distribution in samples of fresh ash taken at different times and at variable distances from the cone. With one exception (sample C–1), the proportion of fine particles increases in samples collected progressively farther from the cone. Figures 13 and 14 are graphs showing the size distribution of the material in samples of fresh ash collected on the same day (October 11, 1946), when variable winds were strongest from the south and somewhat less strong from the east.

A thoroughly mixed sample of the whole thickness of ash mantle was obtained at a place where the mantle was about half a meter thick; when compared with two mixed samples of the top half meter of ash obtained where the mantle was many meters thick, the first sample proved to contain a slightly smaller proportion of coarse particles, but the difference, as shown in table 8, was not as great as might have been expected.

TABLE 8.—*Size distribution of particles in mixed samples of ash from Parícutin taken at three localities*

Locality	Distance and direction from cone	Thickness of entire ash mantle (meters)	Thickness of ash taken in mixed sample (meters)	Constituents in mixed sample (percent)			
				Gravel size	Coarse-sand size	Medium- to fine-sand size	Silt-and clay size
Cocjarao	1 km. to the southwest.	6.0	0.5 (top)	7.5	38.2	43.3	11.0
Jarátiro	1.5 km. to the north.	4.0	0.5 (top)	5.2	34.1	51.9	8.8
Cuezeño	5 km. to the north	.5	0.5 (all)	4.7	30.1	54.1	11.1

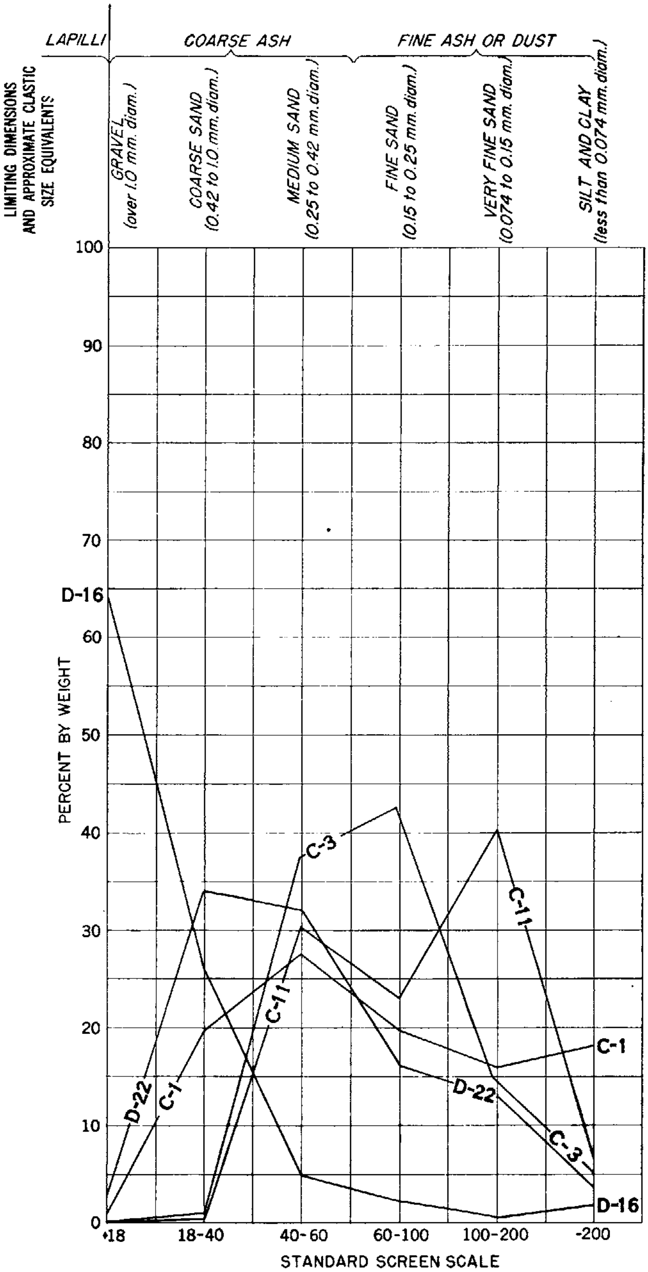


FIGURE 12.—Graph showing size distribution of particles in samples of fresh ash collected in the vicinity of Parícutin.

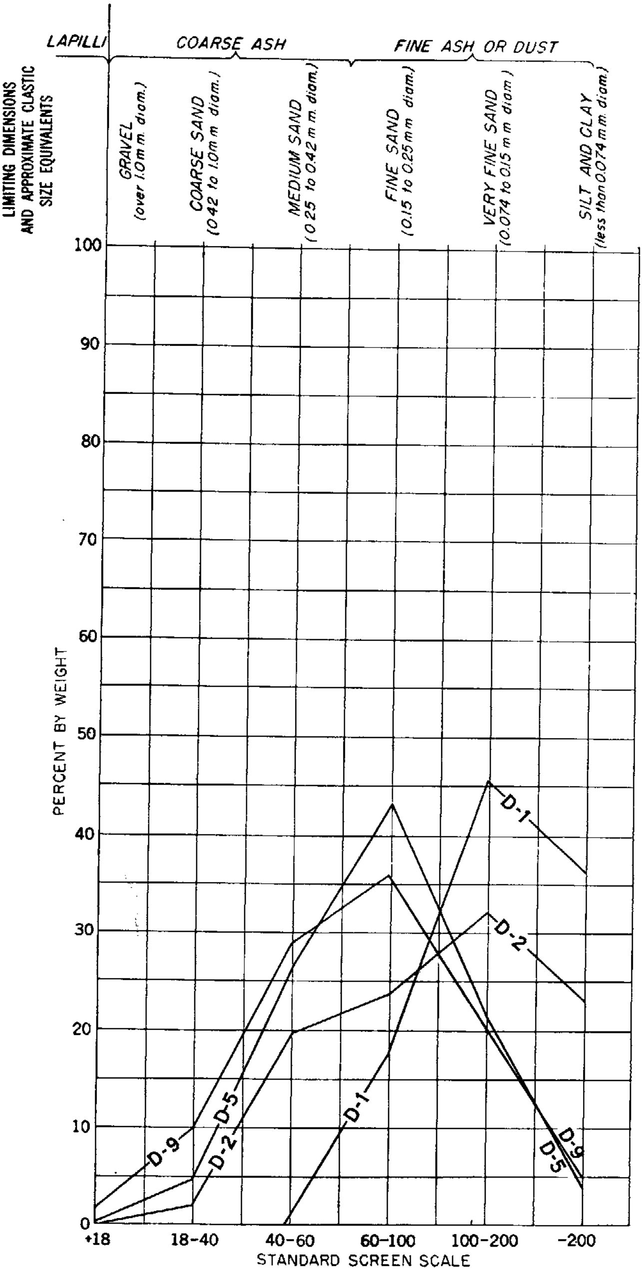


FIGURE 13.—Graph showing size distribution of particles in samples of newly fallen ash collected north and northwest of the Parícutin cone on October 11, 1946.

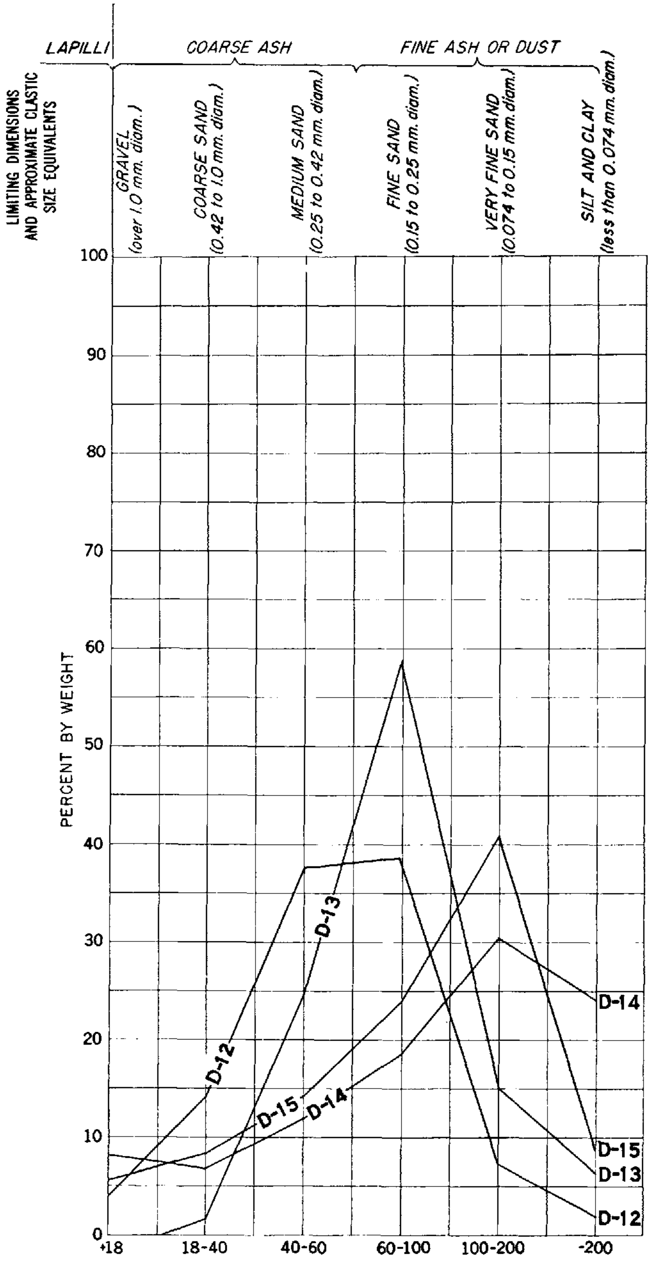


FIGURE 14.—Graph showing size distribution of particles in samples of newly fallen ash collected north and east of the Parícutin cone on October 11, 1946.

The size distribution of the particles in the mixed samples described in table 8 is shown graphically in figure 15. If it were possible to obtain representative samples of the entire 4-meter thickness of ash at Jarátiro and the 6-meter thickness at Cocjarao, these would undoubtedly show much higher percentages of very coarse material than the mixed sample of the entire ash mantle taken at Cuezeño because of the greater force of the eruption during the first year or two of activity. It appears, therefore, that ash from more recent, weaker eruptions is being deposited very near the cone and that this closely resembles in its size distribution the entire ash mantle deposited 5 kilometers north of the cone.

EFFECT OF ASH ON VEGETATION

The ash killed most of the trees and buried all the smaller plants within a radius of several kilometers from the volcano, the fine dust sealing the pores of the leaves and preventing respiration and transpiration. The ash adhered most readily to sticky surfaces, such as the needles of conifers; moreover, the weight of the ash cover broke the tree tops and branches. The resinous pines were, therefore, destroyed over a larger area than the oaks, and the more brittle, stiff old pines were killed before the limber young trees, which were arched by the ash weight but could shake off the load in a wind. According to Arias Portillo,[38] the damage in general has been directly proportional to the kind and number of "accessories" a plant possesses, such as hair, down or nap, and thorns, as well as the stickiness of the substances secreted. The least-damaged agricultural crops were wheat and barley, but regardless of the nature of the plant the destruction was complete where the ash cover was thick.

Within the 1-meter isopach (pl. 1), which encircles a roughly elliptical area about 10.5 kilometers long and 7 kilometers wide around the volcano, all the vegetation has been destroyed by the lava or ash except a very few of the hardiest trees (chiefly oak) and still fewer young pines. The old mantle of pine needles, which served to retard runoff and erosion, is deeply buried beneath the ash, and the rain water that runs down the trunks of the dead trees can initiate rills and channels, thus greatly accelerating erosion.

The 0.25-meter isopach encloses a much larger elliptical area, 20 kilometers long by 15 kilometers wide, which includes a zone of semidevastation that surrounds the completely devastated zone. In this zone of semidevastation the ash is so thick that the fields cannot be cultivated unless it is first removed or the soil can be brought to the surface by deep plowing. Although the largest pines were killed

[38] Arias Portillo, Pedro, La región devastada por el volcán de Parícutin: mimeographed thesis, Escuela Nacional de Agricultura, pp. 21-22, Chapingo, Mexico 1945

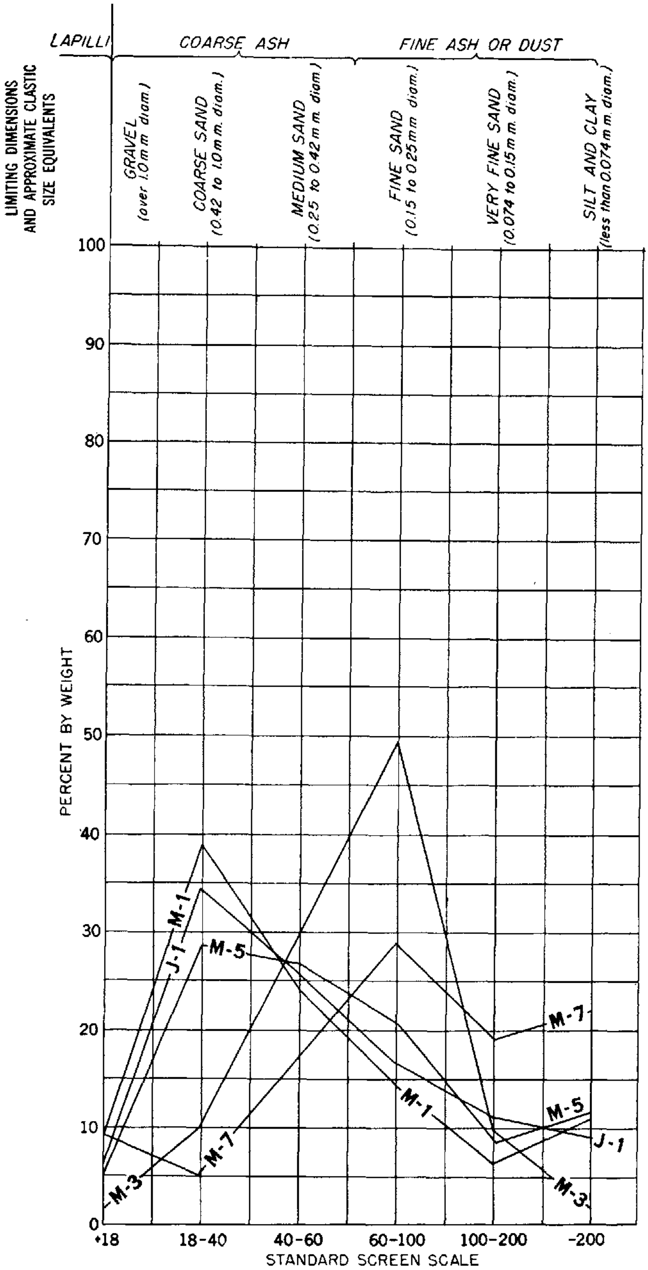


FIGURE 15.—Graph showing size distribution of particles in ash from Parícutin. Samples are from infiltration-test cores taken to a depth of half a meter from the surface.

soon after the eruption began, most of the other trees are still living The grasses and other small plants are gone except on some of the steepest slopes where the ash has been stripped off. Pine needles still fall in this area and hold back some runoff, but erosion has been accelerated by the absence of a grass cover.

POROSITY AND PERMEABILITY OF ASH MANTLE

The ash is so loose when it first falls that one sinks from 2 to 4 centimeters into it while walking, but the rains compact it to the extent that, when the ash is damp, an automobile may pass over it and leave only faint tire impressions. Much of this surface compactness is destroyed during the dry season, when walking is difficult and cars cannot be driven off the roads with safety. Even then, however, moisture is retained several centimeters below the surface.

According to studies made by Rollin Eckis in southern California, "porosity of natural coarse sediments does not depend upon the size of material, as coarser materials have more grade sizes (poorer sorting) and hence lower porosity." [39] This principle does not appear to be applicable at Parícutin, however, probably because the ash is better sorted than the alluvial deposits described by Eckis. The porosity and permeability of the ash cover seem to depend, not only on the degree of wetness or dryness, but also on grain size and degree of sorting. Small grains can be more closely compacted than large ones if degree of sorting is equal, and this fact in itself affects drying, causing fine-grained, well-sorted beds to dry more slowly than coarse-grained, well-sorted beds. Poorly sorted beds dry still more slowly. Moreover, the arrangement of beds within a given section of ash may greatly affect the permeability of the section; the presence of fine material at or near the top, for example, may slow down the intake of rain water at the surface. The preexisting soil mantle is less permeable than the ash from Parícutin, largely because of the reduction in particle size effected by weathering.

There is no evidence that the filling of interstitial spaces by precipitated salts or the very minor compaction that may result from earthquakes appreciably affects the permeability of the Parícutin mantle.

INFILTRATION TESTS

Table 9 gives the results of infiltration tests in ash and preexisting soil carried on at four places near the volcano at different times during 1946 and 1947.

[39] Tolman, C. F., Ground water, p. 113, New York, 1937.

TABLE 9.—*Results of infiltration tests in ash from Parícutin and preexisting soil*

[In millimeters]

Time (minutes)	Cumulative absorption of water					
	At Cuezeño			At Jarátiro	At Cocjarao	At Llano Grande
	A	B	C	D	E	F
	Mean of 4 tests in preexisting soil, Nov. 29–Dec. 1, 1946 [1]	Mean of 4 tests in ash, Nov. 28–30, 1946 [1]	Mean of 2 tests in ash, Feb. 26–27, 1947 [2]	Mean of 2 tests in ash, Feb. 23, 1947 [2]	Mean of 2 tests in ash, Mar. 1, 1947 [2]	Mean of 2 tests in dune ash, Mar. 4, 1947 [2]
10	8.2	15.8	22.0	29.1	21.7	64.0
20	12.0	21.5	28.9	40.8	26.7	99.0
30	15.6	28.3	35.2	46.6	32.8	139.7
60	24.8	44.9	55.7	60.8	46.8	250.4
90	34.6	60.8	74.7	78.3	57.2	(3)
120	44.9	75.8	89.6	95.8	67.8	(3)
150	55.9	88.7	[4] 102.6	[5] 110.8	78.3	(3)
180	66.9	103.7	114.6	128.3	87.2	(3)
210	76.8	117.8	127.3	145.8	[6] 96.6	(3)

[1] At end of rainy season.
[2] During dry season.
[3] Discontinued.
[4] Time required for water to pass through top 50 centimeters of ash, 165 minutes.
[5] Time required for water to pass through top 50 centimeters of ash, 150 minutes.
[6] Time required for water to pass through top 50 centimeters of ash, 240 minutes.

The method followed was a slight modification of that used by G. W. Musgrave.[40] Galvanized sheet-metal tubes 55 centimeters long and of two different diameters (6 inches for tests A and B; 8 inches for C, D, E, and F), sealed along the seam, were driven vertically downward through the top 50 centimeters of ash or preexisting soil by means of an automobile jack working against a log suspended horizontally between heavy posts. During each operation the tube was kept vertical by checking it frequently with a plumb line; if it went out of plumb (usually because of an obstruction), it was pulled out and either discarded (if bent) or driven down at a new site.

When a pair of tubes was satisfactorily set in the ground with only the top 5 centimeters of each protruding above the surface, the jack was removed and a glass tube 16.6 millimeters in diameter and 90 centimeters long was supported vertically over the center of each confined column. Through a petcock at the bottom of each tube, measured amounts of water were allowed to drip onto the surface of the enclosed column, but only as fast as the water was absorbed. A perforated metal disk placed on this surface and a rubber hose leading from the petcock almost to the disk prevented turbidity due to splashing. Every 10 minutes during the first half hour, and at half-hour intervals during the next 3 hours, the amount of water consumed was recorded.

[40] Musgrave, G. W., The infiltration capacity of soils in relation to the control of surface run-off and erosion: Am. Soc. Agronomy Jour., vol. 27, pp. 336–345, 1935.

For tests C, D, and E, a second set of tubes was driven nearby, and the lower end of each was exposed by excavating along one side. Water was added to both sets at the same rate; the second set was then used to determine the time required for the water to pass through the entire column. (In the case of E, the test time had to be extended, as it took the water 4 hours to pass through the column.) At the conclusion of tests C, D, E, and F, the ash column was removed from each tube, and a representative sample of all the material contained was taken for screening tests, whose results are shown graphically in figure 15. The results of the infiltration tests were calculated to surface millimeters of water, taking the mean for each set of tubes and reducing the values in accordance with the diameter of each column.

Tests A and B were made at the close of the rainy season; hence the ash was very damp even at the surface. Tests C, D, E, and F were made in the middle of the dry season, when there had been no rain for weeks. In test C, ground damp began 8 centimeters below the surface; in test D, 6 centimeters; in test E, 3 centimeters. In test F, the loose fresh dune ash was dry beyond the depth of the test.

The infiltration-test results (fig. 16) show that at Cuezeño, during the rainy season, the infiltration of water into the ash during the first 10 minutes was 93 percent greater than into the underlying soil at the same place and at the same time; also, that the infiltration into the ash in 10 minutes was 49 percent greater during the dry season than during the wet season, although at the end of 3½ hours it was only 8 percent greater. During the dry season, the infiltration for the first 10 minutes was 32 percent greater at Jarátiro and 191 percent greater at Llano Grande than at Cuezeño. At Cocjarao the infiltration in the first 10 minutes was about the same as at Cuezeño, although for the full period of 3½ hours it was 23 percent less.

The percentages, by volume, of water added to produce saturation of the enclosed ash columns showed close agreement at Cuezeño, Jarátiro, and Cocjarao: 20.5, 22.2, and 21.2, respectively. Initial dampness was approximately the same for the three columns (tests C, D, and E); hence it can be assumed that their average porosities were nearly equal. The different infiltration rates obtained in the three tests are due, apparently, to factors other than differences in the average porosities of the 50-centimeter enclosed columns.

The unbedded and unusually well sorted nature of the dune ash at Llano Grande accounts for the more rapid infiltration here than at Cuezeño. At Jarátiro, although the average grain size was appreciably larger, the degree of sorting was about the same. The average grain size at Cocjarao was a little greater than that at Cuezeño. At Cocjarao, however, a very compact bed of fine material that was damp even in the dry season was encountered only 3.5 centimeters

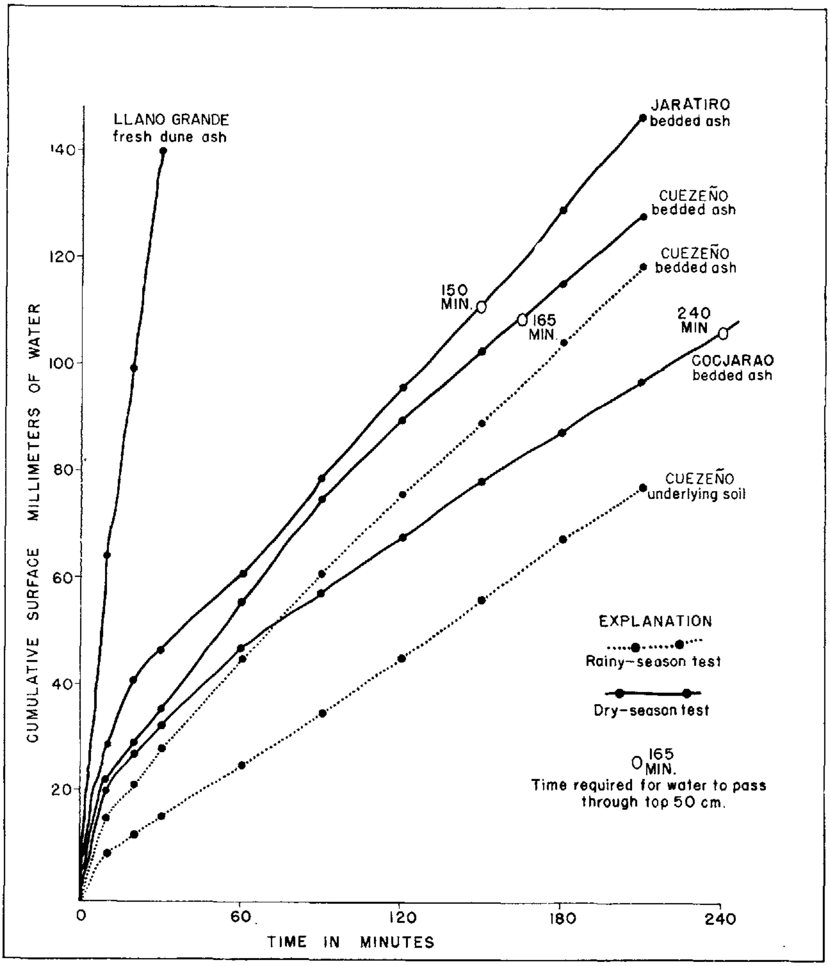


FIGURE 16.—Cumulative infiltration curves for undisturbed ash from Parícutin and preexisting soil.

below the surface, whereas at Cuezeño the bedding was not nearly so pronounced and the dry-season damp line was 7 centimeters below the surface. Thus the distribution of beds within a column affects the permeability to a greater extent than the average grain size and average porosity. As Lowdermilk has pointed out [41] fine material acts as a seal against rapid infiltration; the stratum of fine material at Cocjarao sealed the lower beds of the column in the same way that the weathered preexisting soil retarded infiltration into the subsurface beds.

The Mexican Departamento de Conservación de Suelos reports that

[41] Lowdermilk, W. C., Erosional phenomena associated with volcanic eruption of Parícutin, Mexico: Am. Geophys. Union Trans., vol. 28, p. 270, 1947.

no infiltration tests have been made elsewhere in Mexico; however, the ash from Parícutin can be compared with two American soils that were tested after several days of rainfall by a method [42] comparable to that employed at Parícutin. In the following tabulation, the Shelby soil is a comparatively impermeable silt-loam from Bethany, Mo.; the Marshall soil is a permeable silt-loam from Page County, Iowa; the Cuezeño is an ocher-colored volcanic soil that underlies the ash from Parícutin. Both the Marshall and Cuezeño soils are fairly permeable, but the unweathered ash from Parícutin, despite its fine-grained beds, is much more permeable.

Time (hours)	Cumulative absorption of water (millimeters)		
	Shelby soil	Marshall soil	Cuezeño soil
½	3	18½	15½
1	5½	32	25
3½	8	70	77

In the infiltration tests tabulated above, the surface was covered with a perforated disk to avoid turbidity and compaction from impact of the water fed to the confined column. Falling raindrops vary in size and velocity and hence in the force of their impact. Increasing drop size decreased the infiltration rate at which water passed through other soils tested in the United States by as much as 70 percent.[43] Part of this effect was caused by breaking down the clods of soil and is only in part comparable to the effect on an ash surface.

CRUSTING AND RAIN IMPACT: EFFECT ON RUNOFF

The surface of the Parícutin ash mantle becomes crusted over by a layer that is more compact and less permeable than the underlying material. Ash eroded by the spashing of raindrops and by sheet and channel flow and redeposited in flatter areas remains loose and uncrusted, while the steeper slopes from which the loose particles have been eroded become crusted. The material forming the crust, which is ordinarily only a few millimeters thick, tends to be finer-grained than the underlying layers. This crust is largely the result of turbidity caused by the impact of raindrops and, therefore, the puddling of fine-grained ash. Carl Fries, Jr.,[44] has suggested also that sheet flow is no doubt accompanied by a downward percolation of some of the water flowing over the surface, and it seems likely that the fine particles suspended in this water would be filtered out by the first few millimeters of ash as the water percolated downward. Moreover,

[42] Musgrave, G. W., op. cit., p. 340.
[43] Laws, J. O., Recent studies in raindrops and erosion: Agr. Eng., vol. 21, p. 431–433, 1940.
[44] Personal communication.

the large loose particles that do not fit into interstices as easily as the fine particles would be carried away while the sheet flow was forming.

The permeability of the mantle is so much reduced by the crust that runoff and erosion are rapid over the areas that are "waterproofed" in this manner. However, much of the runoff water sinks in the uncrusted areas, such as the alluvial fans and plains, and this process—coupled with the trapping of drainage by lava flows—may result in less rapid total runoff from the region now than before the eruption.

The ash redeposited by the wind remains uncrusted, whereas the surface of areas where deflation is active becomes crusted. Although the process of winnowing tends to lift the fine material into the atmosphere and disperse it, the wind also tends to roll and pile into ripples and dunes the large loose particles that do not compact as easily as the fine particles. The material between the dunes and ripples is finer-grained than that on their crests. The removal of the loose surface ash by the wind, down to the first compact (generally fine-grained) bed, may account for the crust found in areas of deflation.

At Cuezeño, in areas of sheet deposition where the surface was not crusted, raindrops left steep-walled impact craters whose inner diameter ranged from 1 centimeter to 1.5 centimeters. The tiny craters overlapped each other for the most part, leaving incomplete rims from 2 to 4 millimeters thick that stood in the form of fragile pinnacles as high as 1 centimeter above the crater floor, attesting to the cohesive power of the clay-size fractions in the material of which they were formed. Undestroyed craters had nearly perpendicular inner walls and overhanging outer walls. Most of the ash surface in the area was still wet 15 hours after the latest rainstorm, but in the few places where it had dried, the walls of the tiny craters that could still be recognized had collapsed into low ridges about 8 millimeters wide.

In areas of sheet erosion where the surface was crusted, raindrops produced a honeycomb pattern. Individual cells ranged up to 3 centimeters in diameter, although they averaged only 2 centimeters; the cell walls were about 3 millimeters wide and 1 millimeter high. In other places, the removal of the top centimeter of the ash surface by sheet erosion had exposed a lower layer that was more deeply rain-pitted. A coating of exceptionally fine particles over the surface of these pits, which were about half a centimeter in diameter and depth, gave the pits a glazed appearance. There the falling raindrops must have freed and floated to the surface small quantities of the finest particles.

859358—50——5

BUBBLE MOUNDS

Rarely, small hollow mounds form on the ash surface during the rainy season. On one occasion mounds about 1 centimeter high and from 4 to 9 centimeters in diameter were found on somewhat crusted ash in stream interfluves at Huirambosta. The dome-shaped top of each mound was about 8 millimeters thick, and beneath was a hollow space averaging a little more than 2 centimeters in height. The floor of each hollow was of noticeably coarser material than the dome. These hollow mounds were apparently formed by trapped moist air that rose upward through a coarse stratum, was stopped by the fine-grained surface stratum, and pushed it up into a dome. The distribution of the mounds was somewhat erratic, but where they were most numerous, from five to eight mounds were counted per square meter.

On another occasion mounds averaging nine to the square meter and about 12 centimeters in diameter were noted on the surface of a lacustrine deposit at the edge of the lava just southeast of Cerro de Canicjuata. They were only about 1 millimeter high, however, and their hollow centers were noticeable only because they yielded slightly to the pressure of the foot. The mounds were darker than the spaces between them, as they were damp and the rest of the surface was dry. Apparently the moist air that formed them was escaping slowly through the domes. Other mounds were seen near this lake bed in flat arroyo bottoms and stream interfluves, but apparently none formed on sloping surfaces. In the broad saddle south of Canicjuata, mounds from 30 to 40 centimeters in diameter and 1 meter to 2 meters apart were associated with a few dense colonies of smaller mounds 6 or 7 centimeters in diameter.

One bubble mound seen at Huirambosta was 20 centimeters in diameter and had lifted a fine-grained surface bed 1.5 centimeters thick as much as 2 centimeters above its floor. No other mounds were seen for many meters in any direction.

DIFFERENTIAL DRYING OF ASH

The rate at which the surface of the ash dries out depends on the local relief and on the compactness and permeability of the surface layer. The rate of drying is more rapid if this layer is loose than if it is compact. A coarse-grained surface layer dries more quickly than a fine-grained layer, and such features as crusts, fans, mudflows, current ripples, areas of sheet erosion, areas of redeposition, flow lines in alluvial fans, wind ripples, and other, less common, phenomena have different rates of drying. As wet ash is much darker than dry ash, these features may be distinguished more readily while the surface is drying than when it is entirely wet or dry; thus differential drying makes it possible to photograph forms that would not otherwise appear in a picture (fig. 17).

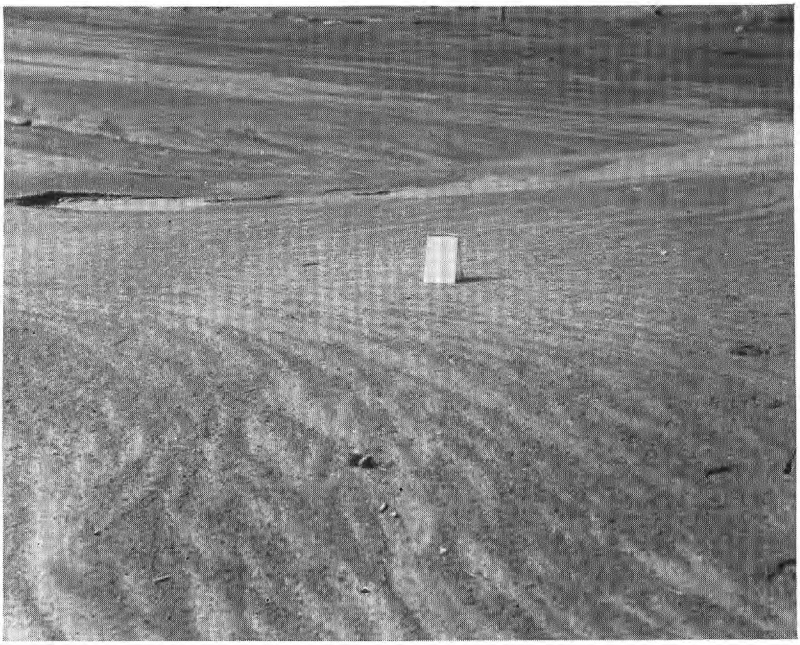


FIGURE 17.—Flow marks on a small alluvial fan at base of Cerro de Capatzun, near Parícutin.

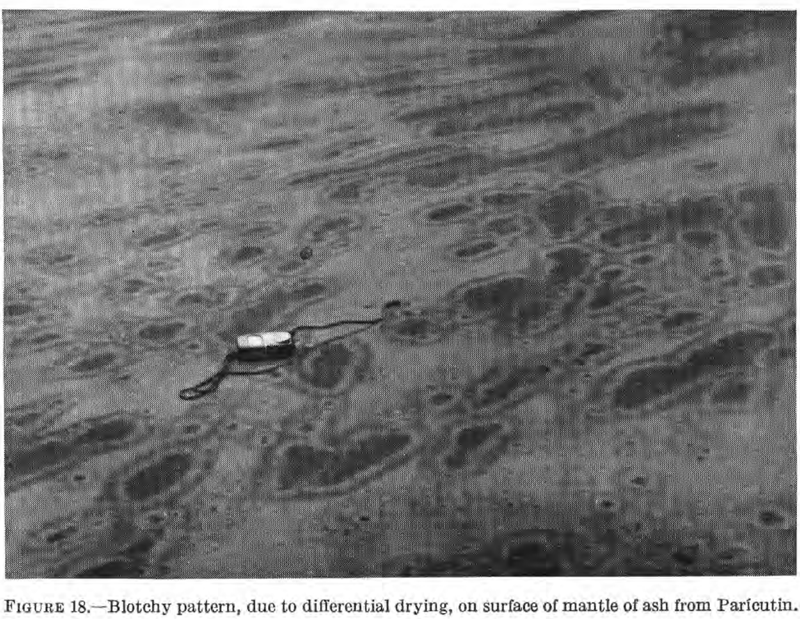


FIGURE 18.—Blotchy pattern, due to differential drying, on surface of mantle of ash from Parícutin.

The escape of moist air from below the surface of the ash also causes differential drying. This is particularly noticeable in areas where bubble mounds have formed or where the escaping air has not lifted the surface layer but merely formed colonies of circular or elliptical blotches, which when partly dried out are dark in the center and lighter around the edge (fig. 18). Ash-covered lava flows also show differential drying, which varies not only from flow to flow but in different parts of the same flow. This difference is due partly to the heat given off by the lava, which helps to dry the overlying ash, and partly to the moist fumarolic gases that escape at places and keep the ash cover wet. Some of the fumarolic salts deposited in the ash on top of new lava are deliquescent and keep the area around them wet for a long time.

EROSION, TRANSPORTATION, AND REDEPOSITION OF ASH

MASS MOVEMENT

CREEP

Where ash-mantled slopes are steeper than 32°, which is near the angle of repose of ash from Parícutin, the trees still standing lean downhill because of the creeping ash mantle. On the 45° slopes on either side of the arroyo bordering the large meander scar described on page 15 (see also fig. 2), the trunks of dead pine trees lean downhill at angles as great as 60° from the vertical, although few have fallen over, probably because of the support afforded by the 3-meter mantle of ash. Farther to the west, where the mantle has been stripped away (as at Queréndaro), all the trees have fallen and are pointing down slope.

On hillsides, such as those on Cerro de Canicjuata, whose slopes were originally about 32° (now lessened in places to 25° or steepened to as much as 40° by landsliding and other causes), the trees stood upright before the eruption. Now they lean. The present, loose, more permeable ash mantle is creeping downhill, owing to lack of compaction and lubrication by water. As shown in figure 19, the leaning on the north slope of Cerro de Canicjuata varies with the topography from a few degrees from the vertical, as on spurs where drainage is adequate, to 90° or more in swales where poor drainage has resulted in a higher degree of saturation of the mantle with a consequent increase in the rate of creep.

LANDSLIDES

Creep is a manifestation of slow landsliding, whereas a landslide in the usual sense is the sudden descent of a large volume of material from a steep slope, leaving a concave wall at the head of the slide (fig. 20). Landslides have stripped the entire ash mantle from large

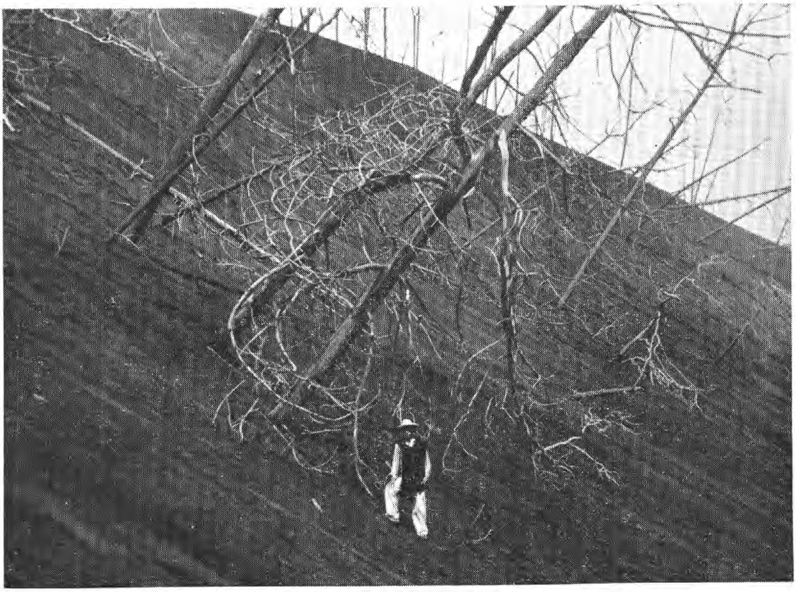


FIGURE 19.—Tilted forest on north slope of Cerro de Canicjuata, near Parícutin.

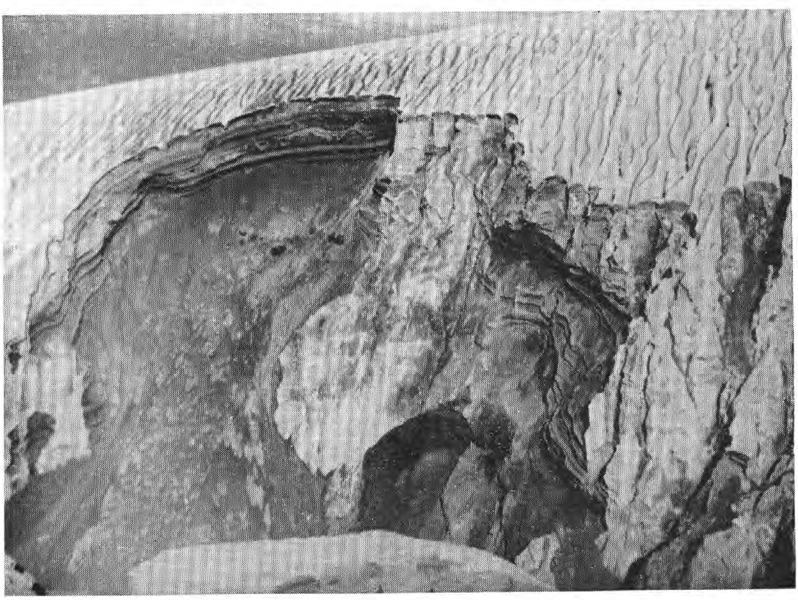


FIGURE 20.—Head wall of a landslide in deep ash from Parícutin.

areas on barranca sides south of Zirosto and left head walls of ash that stand a meter above the stripped surfaces. Closer to the cone, where the ash is several meters thick, landslides are controlled in part by bedding. On the north side of Cerro de Canicjuata, for example, it is common for only the top meter of material above a more resistant bed to be removed by landsliding. That water greatly influences the landslide process can be seen, just after heavy rains, when new landslides occur in places where the toe of a slope is cut by channel erosion and where the mantle uphill from the channel is waterlogged, as indicated by mudflows that ooze from the landslide material.

The trees that remain standing on landslide slopes, even though influenced by slow creep, often serve as bastions of defense against a rapid down slip. This is shown by the presence of a cusp that joins concave head walls on either side of a tree that has served to hold the mantle in place.

MUDFLOWS

Mudflow development in ash from Parícutin results where a coarse-grained or a comparatively well sorted, permeable surface layer absorbs enough water to give it fluidity or lubrication, provided that (1) fine-grained or more poorly sorted, relatively less permeable material below is unable to absorb water at the rate it falls on the surface and (2) the slope angle is great enough to cause movement at the degree of fluidity attained by the surface layer. The flow is in narrow lobes, rather than in broad sheets.

Individual mudflows in the ash range in width from a few millimeters to 2 or 3 meters. Fanlike groups of overlapping flows may be as much as 20 meters wide; indeed, most of the alluvial fans that have formed in the area near the cone consist of mudflow material. The thickness of individual flows ranges from one-fifth to one-half the width. Thus they are small-scale features compared to the modern mudflows of the desert regions of the western United States and the lahars of the Netherlands East Indies or to many ancient mudflows that are part of the geologic record in numerous parts of the world.

In fluidity, the mudflows represent an intermediate stage between creep and sheet wash. A mudflow moves down slope until its fluidity is so reduced by the loss of its water into the underlying permeable ash mantle that the front of the flow comes to a stop. The up-slope part of the flow behind this front continues, but owing to the progressively decreasing gradient as the material moves over the frontal lobe, successive fronts form that stop in receding waves until the movement halts completely. If the flow is relatively large, however, the material behind the stopped fronts may bypass or overrun the fore part (fig. 21), depending largely on the supply of water available for lubrication.

FIGURE 21.—Mudflows between Jarátiro and Parícutin.

FIGURE 22.—Lower end of a low-gradient mudflow in the Parícutin area. Note that the lower part of the furrow has been filled by redeposited material, causing overflow.

Furrows are formed in the centers of mudflows because of the greater fluidity there. These furrows, which are about one-third to one-half the mudflow width, are analogous in some respects to the troughs between lateral moraines of glaciers and also, as Carl Fries, Jr., has suggested, to the troughs left in lava streams as the molten material moves between its chilled sides. While storm discharge is still appreciable but below its maximum, the material that feeds the various lobes of a mudflow may continue downhill long enough to fill the already-formed furrows before all movement ceases (fig. 22). If the storm continues long enough, or perhaps during a storm a day or two later, new flows may form and cover the older mudflows. At times the supply of water is so great that channel stream flow forms and erodes the material deposited by the mudflow (fig. 23). Thus, in a period of weeks or months, a labyrinthine complexity can result (fig. 24).

All the large mudflows form in the coarse-grained, permeable ash mantle near the volcano. Landslides often provide the permeable surface necessary for mudflow development. In general, mudflows form neither on crusted areas nor on uncrusted areas whose slope gradient is slight. On a steep crusted slope along the horse trail to Jarátiro, where the hooves of perhaps 20 horses per day kept a narrow strip broken up, mudflows formed in the trail during each heavy rain, while sheet wash, rilling, and channeling occurred on either side.

Tiny drips of clay-size ash which resemble wax dripping along the

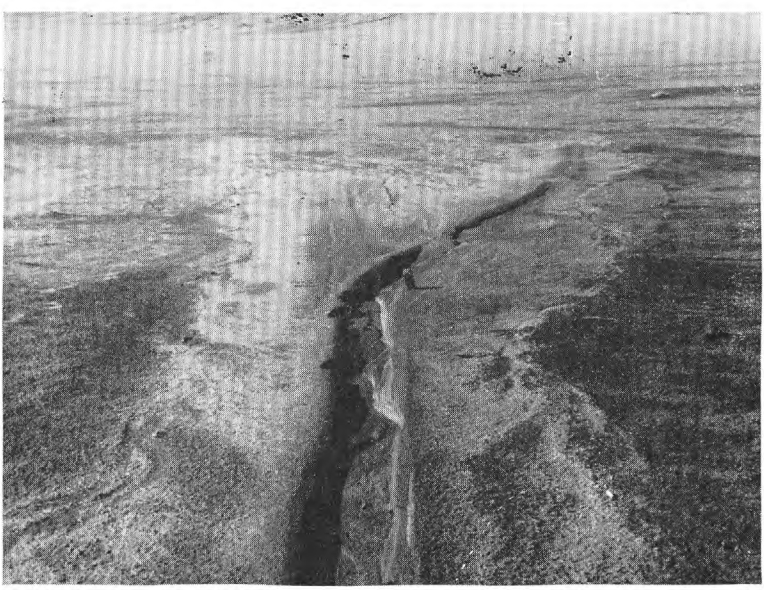


FIGURE 23.—Channel erosion of a mudflow furrow in the Parícutin area.

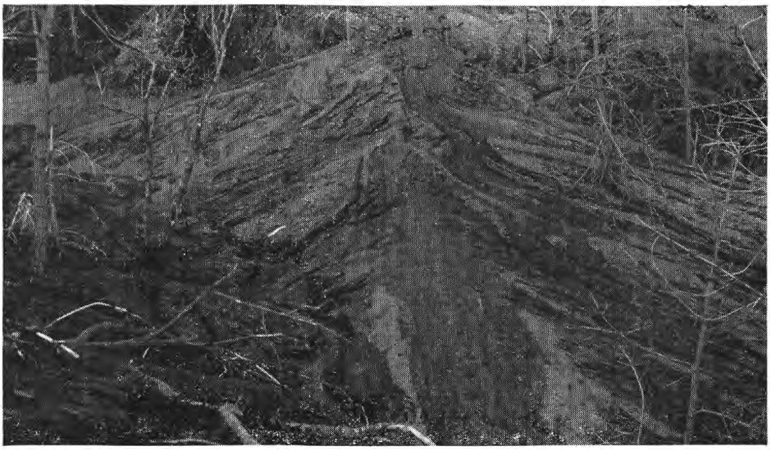


FIGURE 24.—Fan-building mudflow of great complexity at base of Cerro de Corucjuata, near Parícutin.

sides of a candle, leaving blobs part way down and at the base, form on the walls of arroyos even at some distance from the volcano; although only a few millimeters thick individually, they may coat the arroyo wall to a thickness of 1 centimeter or 2 centimeters (fig. 25). Their development is probably caused by raindrop impact and the resulting water suspension of fine material.

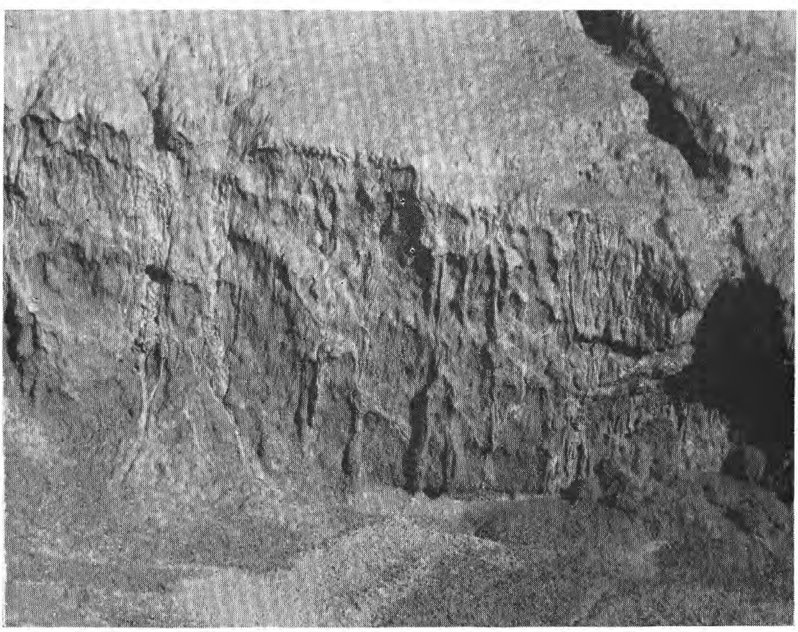


FIGURE 25.—Drips of clay-size ash formed on the vertical bank of an arroyo in the Parícutin area.

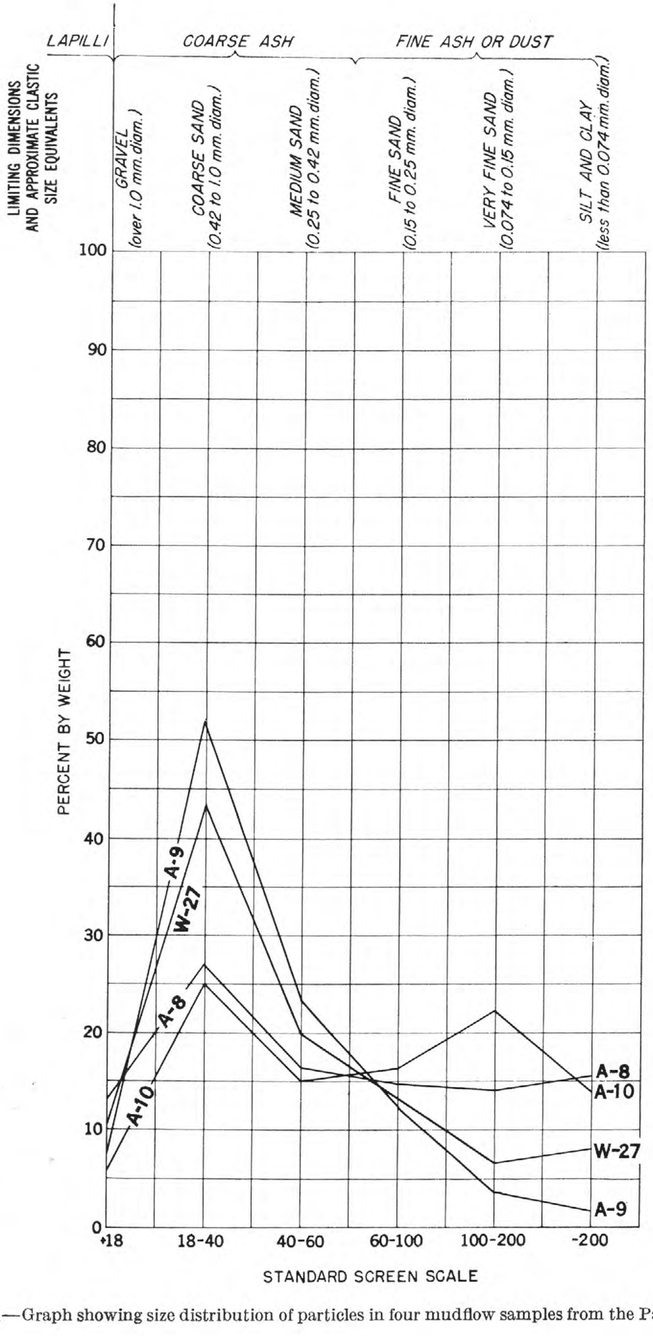


FIGURE 26.—Graph showing size distribution of particles in four mudflow samples from the Parícutin area.

The size distribution of the particles in different mudflows is illustrated graphically in figure 26. Not shown are numerous boulders carried by flows. The curves for the flows formed near the cone show a peak for the coarse-sand-size fraction, whereas the drips of clay-size ash on arroyo walls are composed of very fine particles.

Mudflow velocities vary greatly. The frontal lobe of a flow 6 centimeters wide was observed to travel 4 meters in 6 seconds on a 25-percent grade. A minute later, the lobe came to a halt at a 15-percent grade, flowing the last 65 centimeters in 8 seconds. Another mudflow from 1 meter to 2 meters wide pushed its front over the last 15 meters of its course in 90 seconds on a grade ranging from 15 to 12 percent. The maximum speed may be considered to approach that of water running down an equal slope.

The height of the column of relatively clear water remaining after the sediment had settled in a cylindrical flask of mudflow material, collected while flowing, varied from 5 to 19 percent of the total height of the sample. Samples taken from silt-laden floods in the upper part of the Río de Itzícuaro contained similar proportions of water, but the minimum water content was somewhat greater, amounting to 11 percent by volume. As one such flood receded, mud ridgelets 2 or 3 millimeters high and parallel to the direction of stream flow were left along the banks, together with pockets of ooze at the edges of the stream (fig. 27). However, the sediment-laden stream showed

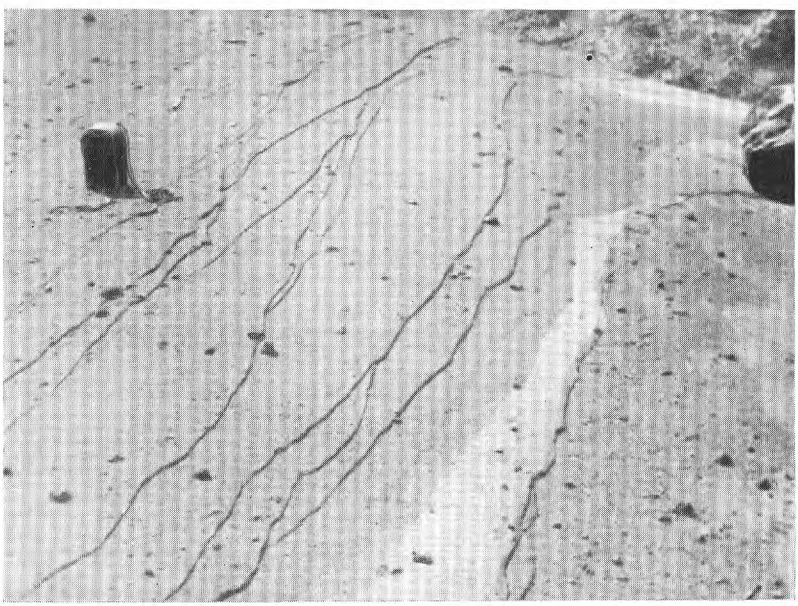


FIGURE 27.—Tiny ridges of mud left on the bank of the Río de Itzícuaro, west of Parícutin, by a waning flood.

none of the other characteristics of mudflows, such as lobe forming, apparently because its great volume was confined and kept rapidly flowing between narrow channel walls and there was a relatively small absorption of water into the stream bed.

Mudflow deposits are not stratified in nearly parallel beds, but have highly irregular lenticular structure. The alluvial fan at the mouth of Arroyo de Corucjuata, near Sinámichu, has been wrongly considered to be a mudflow; its unmistakable bedding, as shown in the walls of a barranca that dissects it, proves otherwise.

STREAM-BANK CAVE-INS

The banks of arroyos frequently cave because of the removal of material from their bases by flowing streams.

If the stream flows at the very base of a nearly vertical or slightly overhanging bank, cutting into and undermining the base, a slice breaks off that leaves an indentation, concave toward the stream, whose walls are nearly vertical. At times, however, the central part of the slice remains standing in the form of a rectangular block (fig. 28). Narrow segments break off on either side of such central

FIGURE 28.—Bank cave-in on Arroyo de Ticuiro, near Parícutin.

blocks along fractures that develop normal to the direction of the stream. The central blocks may later collapse, or the cracks may be filled with water-deposited ash.

Where the base of a bank consists of an angle-of-repose slope of loose material and the stream, unable to undermine the bank directly, only carries off some of this loose material, a complete concave slice does not form. Instead, oblique tension cracks form stepwise along the top edge of the bank as if concave slices were about to form. Apparently the full concave slice cannot develop because the material at the bottom of the bank supports the central part of the slice, and only small oblique blocks break off from the leading edge of the incipient slice (fig. 29).

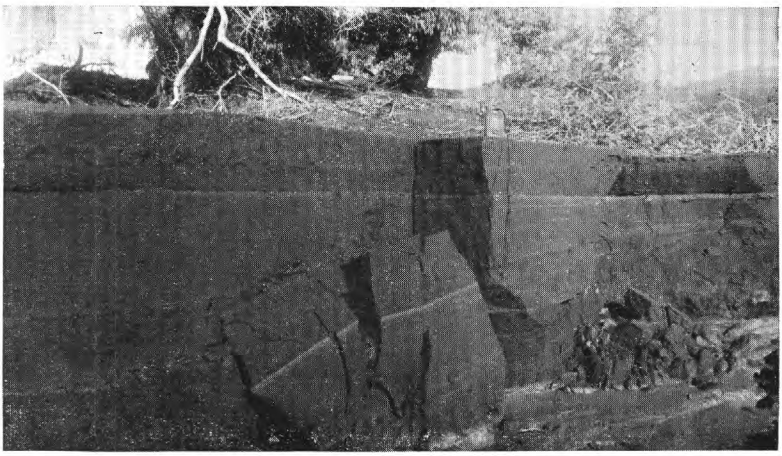


FIGURE 29.—Angular blocks left by stepwise caving along the bank of Arroyo de Corucjuata, in the Parícutin area.

Off the west bank of Arroyo de Ticuiro, shortly after a hard rain, arcuate slices fell for 15 minutes, one after another, along a course 200 meters long. The caved slices averaged 1.2 meters in length, 16 centimeters in thickness, and about 80 centimeters in height. The indentations left by these cave-ins were nearly perfect arcs, and their great number gave the bank a scalloped appearance. In some places curved cracks formed on top of the bank and outlined incipient cave-ins, some of which broke off a few minutes after the cracks formed.

Judging from observations made along several other arroyos, large and small, both the length and thickness of a caved slice are functions of the height of the bank and the relative competency of the material. The ratio between thickness (measured across the middle of the slice in a horizontal direction normal to stream flow), height, and length for most caved slices is about 2 : 3 : 9, indicating a uniform competency of material. Bends in the arroyos were found to change this ratio, and where the bank height has been reduced by deposition or increased by erosion after the caving, its ratio to the thickness and length of the caved slices is of course changed. Overlapping of cave-ins reduces the apparent thickness as well as the length of the slices.

FAULTING OF ASH DUE TO LAVA MOVEMENT

Apart from the faulting and slumping caused by lava movement beneath the cone itself (p. 30), rupture of the ash mantle away from the cone of Parícutin may occur (1) on top of lava flows, (2) beneath new flows, and (3) at the sides of flows.

On the sides of the high, ash-covered lava domes known as Las Pirámides, half a kilometer north of the cone, parallel vertical faults more than 50 meters long were formed in the ash. Vertical displacements up to half a meter in magnitude were not unusual. At one place a long block had dropped across a sloping surface, forming a hillside graben about 2 meters wide. The displacement on the uphill side of the graben was 50 centimeters; that on the downhill side, 15 centimeters. Thin vapors rose from the fault fissures, indicating the presence below of hot lava, whose movement had probably caused the faulting. Parallel rill channels on a slope within a faulted zone either were deflected along faults, ended in open fissures or the loose material that filled them, or—crossing the faults—received short tributaries from along the fault lines.

Where barrancas at the edge of the lava field are cut deep enough to expose a thick section, the ash mantle under the lava is found to be faulted in places, indicating that the lava load was not uniform. A nearly vertical displacement of about 30 centimeters was seen in ash several meters thick under a lava flow near the north base of Cerro de Canicjuata.

At the edges of moving lava, thrust faults frequently form in the top layers of ash that are pushed out from the lava. The observed thickness of the thrust layers ranged from a few millimeters, where only the top crust was involved, to 6 or 7 centimeters, where groups of beds were pushed forward (fig. 30). The observed displacement along the thrust planes ranged from a few centimeters to half a meter. One layer 1.5 centimeters thick was thrust forward 6 centimeters from the edge of the new lava; it rose 1.2 centimeters above the thrust plane, apparently because of support by loose particles that dropped into the space beneath. Stresses in this overhanging plate caused vertical cracking in three places.

In ash-mantled slopes adjacent to new lava flows, series of cracks commonly form. Oriented approximately parallel to the edge of the flow, these cracks are due to tension brought about by the weight of the advancing lava on top of the ash mantle, causing its compaction. Near the steeply sloping north base of Cerro de Canicjuata, parallel tension cracks 2 or 3 millimeters wide were formed in the ash near a

FIGURE 30.—Thrust fault in the top beds of ash from Parícutin along the front of a slowly moving lava flow at Huirambosta.

new flow. They were spaced from 0.5 meter to 1.3 meters apart in a zone extending as much as 15 meters above the edge of the lava (fig. 31). This slope was marked by a succession of small gentle swales, each about half a meter wide and 10 to 20 centimeters deep. Some of the tension cracks crossed one or more of these swales without losing their continuity, but several ended in the middle of one swale and others began stepwise several centimeters up the slope. On the uphill side of a large log lying obliquely across the slope and nearly buried by ash, the tension cracks were short and arranged en echelon.

On the steep east slope of Canicjuata, about 50 or 60 meters above the lava edge and roughly parallel to it, a single fault fissure several hundred meters long appeared. The width of this fissure averaged 2 centimeters, and the throw on the downhill side was 2 centimeters. Where the fault crossed a spur ridge, it curved up slope without interruption, but where it crossed a swale it swung sharply downhill in a broken-step pattern. Then it swung back uphill for the next spur crossing. Tensional stresses set up by the weight of a new lava flow at the foot of the slope probably caused the faulting, although it may have been caused by differential creep of the lower and upper slopes.

WATER EROSION

RAINDROP SPLASH AND SHEET EROSION

Sheet flow occurs when the rate of precipitation exceeds the coincident infiltration capacity of the mantle, and sheet erosion occurs

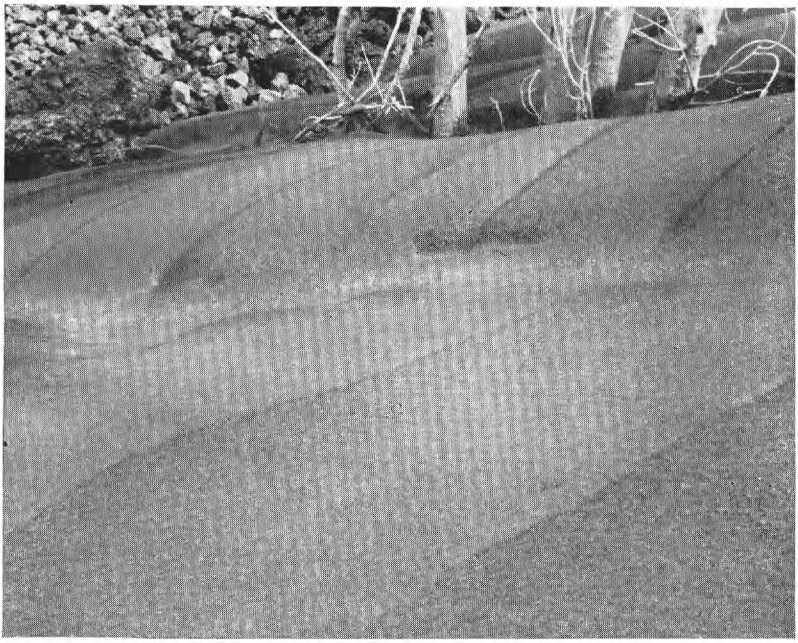


FIGURE 31.—Tension cracks in the mantle of ash from Parícutin produced by the weight of the adjacent lava flow.

when the excess produces an erosive force greater than the initial resistance of the mantle to erosion.[45] Initial resistance in the Parícutin mantle depends on the degree and length of slope and on particle size and compactness, which affect both the amount of ash splashed by rain impact and the amount that flows in a sheet of water. Small rock-capped pedestals left after raindrops have splashed away the ash around their bases show the degree of erosion effected by impact (fig. 32). During heavy rainstorms distant slopes lose their drab, gray appearance briefly and shine in the dull light like lakes or ponds because of the presence of a thin sheet of water. If the sun breaks through the clouds and strikes a place where sheet flow is occurring, the water gleams white like snow or hail. On surfaces of low slope gradient, where sheet flow is quite slow, water piles up to a depth of half a centimeter or more.

According to the experimentally determined infiltration rates in table 9 and figure 16, sheet flow—given sufficient slope gradient—would start during the rainy season at Cuezeño, for example, when the rate of precipitation exceeded 16 millimeters in the first 10 minutes of a storm, 22 millimeters in the first 20 minutes, or 28 millimeters in the first half hour. The high degree of turbidity caused by raindrop

[45] Horton, R. E., Discussion of dynamics of water erosion on land surfaces: Am. Geophys. Union 22d Ann. Mtg., pt. 2, p. 301, 1941.

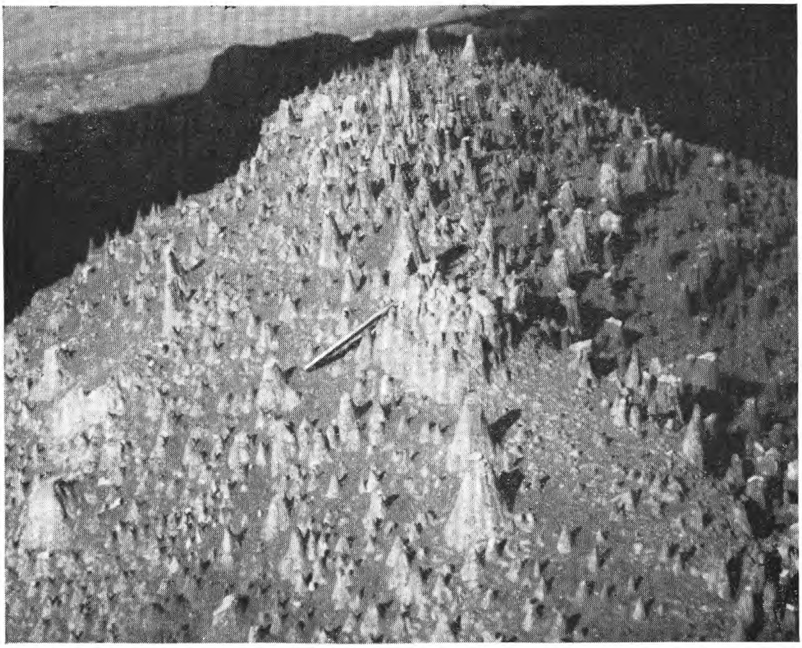


FIGURE 32.—Small bits of broken rock thrown on top of ash from Parícutin at the side of a road have prevented splashing raindrops from eroding the ash underneath them.

impact, however, would reduce the permeability from the experimentally determined figures (turbidity was eliminated in the tests), so that sheet flow would actually start at a lower rate of precipitation. Sheet flow occurred on the ash at Cuezeño when approximately 10 millimeters of rain had fallen in the first 10 minutes of a storm, and it is possible that under special conditions an even lower rate of precipitation might produce sheet flow there.

A belt of no erosion includes the relatively level land at the crest of a slope. W. D. Ellison has pointed out that, on level land, particles splashed by raindrop impact tend to bounce back and forth without shifting the position of the mantle. Particles lifted into the air are replaced by the effect of nearby raindrops. On a slope, however, the splashes move more particles downhill than uphill, so that erosion results.[46] Sheet flow transports the splash-eroded particles and further erodes by abrading the ash surface.

The vegetation cover is of prime importance in reducing both the amount of splash and the intensity of sheet erosion farther down slope. By reducing raindrop impact, a protective cover also reduces turbidity

[46] Ellison, W. D., Erosion by raindrop: Sci. Am., vol. 179, no. 5, pp. 40–45, November 1948; Some effects of raindrops and surface flow on soil erosion and infiltration: Am. Geophys. Union Trans., vol. 26, p. 425, 1945.

and its effect on surface permeability. In the devastated zone around Parícutin, not only was all the vegetation killed, but the humus and all the biologic structures that play an important role in resistance to erosion were deeply buried (except trees, which under these conditions help to start rills).

Sheet erosion, including the antecedent effects of raindrop splashes, gives way in part to channel erosion where the slope steepens, but it continues on the interfluves between the channels all the way down to where the grade is so much reduced that deposition takes place. In well-drained basins throughout the world where the total stream area is approximately 1 percent of the total surface, sheet erosion is of much greater magnitude than channel erosion.[47] In the Parícutin mantle the percentage of channel-erosion area varies with the slope and microtopography from more than 50 percent south and west of the cone to less than 1 percent north of the cone; hence, over much of the region, the percentage of interfluve area where sheet erosion takes place is much smaller than usual (fig. 33).

Nevertheless, a large proportion of the ash eroded from the region has been stripped off by sheet flow (the antecedent effects of raindrop splashes were not determined separately). This proportion was calcu-

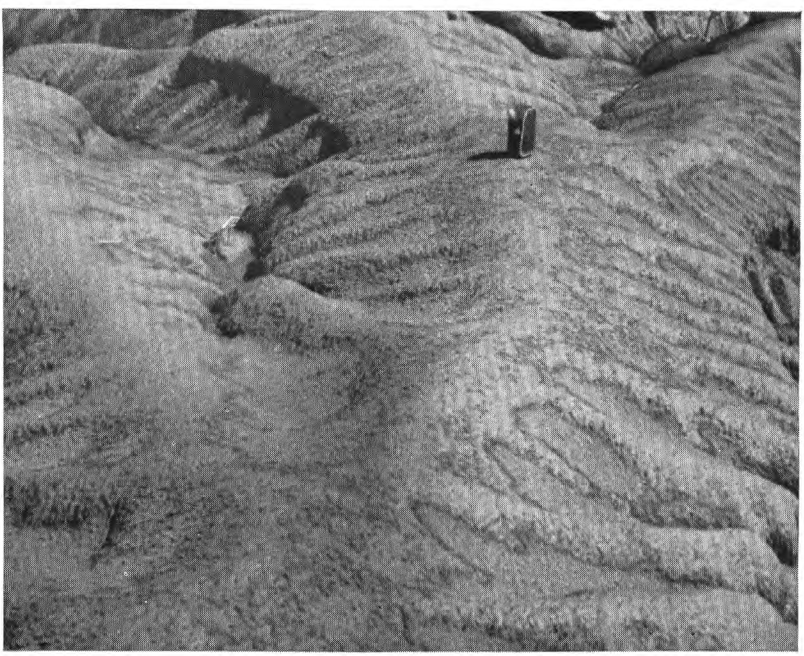


FIGURE 33.—Converging rill heads at crest of a ridge about 2 kilometers south of Parícutin, where the ash is very thick.

[47] Horton, R. E., op. cit., p. 300.

lated by measuring the thickness of the ash on uneroded crests and comparing it with the thickness measured on vertical sections on nearby unchanneled slopes and sloping interfluves. In the choice of sites for measurement, an attempt was made to eliminate all highly local factors such as abnormal slope changes due to rocks and fallen logs, miniature terraces formed behind such obstructions, or changes due to wind erosion and redeposition on open surfaces (as at Llano Grande). The measurements on vertical sections made in different localities are given in table 10.

TABLE 10.—*Proportion of original mantle of ash from Parícutin removed by sheet erosion at different localities up to September 1946*

Locality	Microtopography	Thickness of ash on uneroded crests (centimeters)	Thickness[1] of ash on sheet-eroded surfaces (centimeters)	Percentage of ash removed by sheet erosion
Huanárucua	Midway up slope 500 m. long. Formerly cultivated field. Gradient, about 15 percent.	25	13	48
East of Angahuan	Throughout short slopes 100 to 200 m. long except at very bottom, where sheet deposition has taken place. Formerly pasture land; no trees. Gradient, 36 percent to 50 percent.	25	0	100
Curitzerán	Short distance above bottom of slope about 100 m. long inside crater. Densely wooded with living pines; smaller plants buried, although many pine needles on surface. Gradient, about 60 percent.	28	16	43
Tzintzungo	Near bottom of slope 50 to 100 m. long on interfluves inside crater. Only a few scattered pines and oaks; very little litter. Gradient, about 60 percent.	33	8–10	70
Cutzato	Middle of 30 m. of barren slope below 30 m. of densely wooded slope on north slope inside crater. Gradient, about 60 percent.	38	20	47
Do	Middle of western outer slope about 600 m. long. Wooded with living trees and much underbrush. Gradient, 60 percent.	44	35	20
Near Capánguito	Throughout slope distance of 30 m. below slope 250 m. long, all at 10-percent gradient. Barren.	60	40–47	22–33
Do	Throughout slope distance of 100 m. at 14-percent gradient below slope 250 m. long at 10-percent gradient. All barren.	60	34–42	30–43
Sicuín	Two-thirds down 120-m. southeast slope. Moderate density of pines, two-thirds living, one-third dead. Gradient, 60 percent.	63	32	50
Cuaxándaran	Two-thirds down 600-m. northeast slope. Moderate density of dead but standing tree trunks. Gradient, 60 percent.	165	110	33

[1] All thicknesses were measured on vertical sections and are comparable for this purpose regardless of the inclination of the deposit.

Sheet erosion and deposition occur simultaneously on gentle slopes. On Llano de Huirambosta a surface sloping 3 to 4 percent, for the most part, on which there was no vegetation living or dead, was studied after a heavy rain, during which the capacity of the surface to absorb water had been exceeded and sheet wash—or possibly a gradation into rill-type erosion and deposition—had taken place. Differential drying had accentuated a crisscross pattern that extended from a line 20 or 30 meters below the top of the slope downward for about 50 meters toward a stream channel. The pattern revealed that tiny parallel streams about 1 meter apart had eroded narrow channels not more than half a centimeter deep and half a meter long before dropping their load of suspended matter in miniature fans about 20 centimeters wide and half a centimeter thick. The fans could be distinguished only because their comparatively loose grains had dried and assumed a lighter color than the surrounding material, which was still damp. From the slightly steeper slopes of the fans, small distributaries had taken off to one side, down the steeper component of slope, and in turn made their own tracks, which were oriented obliquely to the main channels. But the main streams reappeared below the fans and continued straight on down the slope. Only where material was deposited did distributaries form that crossed the slope obliquely and thus produced the crisscross pattern. Parallelograms formed in this manner had sides 60 centimeters to a little more than 1 meter long and angles of approximately 30° and 60° (fig. 34).

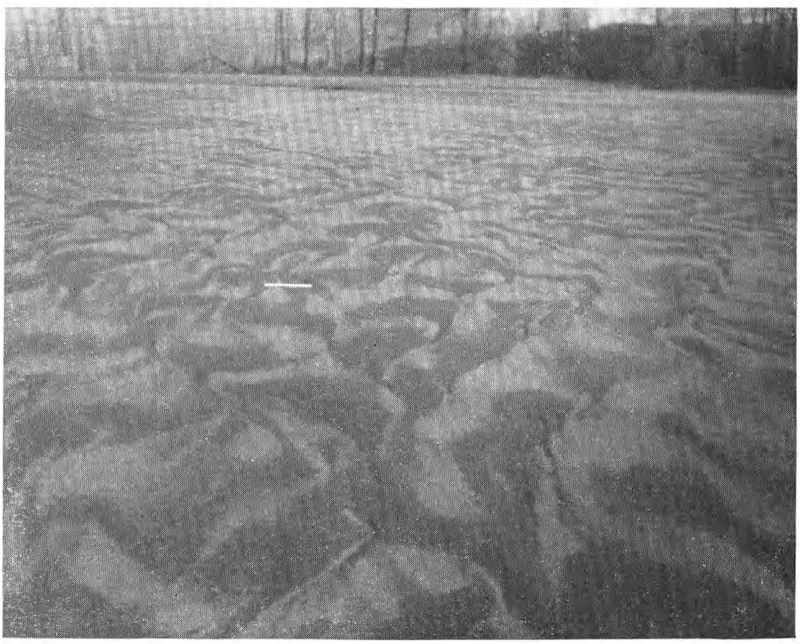


FIGURE 34.—Parallelogram pattern of sheet wash at Huirambosta, near Parícutin.

Farther down this same slope the main channels and distributary tracks became wider. Although they were not much deeper at first, they began to coalesce and form shallow braided channels, which continued to deepen until they joined the arroyo below. Some of the interfluves between the deepening channels were marked with the same crisscross pattern of sheet erosion and deposition that had developed on the upper slope.

After a much lighter rain a few days later, rain prints covered Llano de Huirambosta except at a few places where the slope was much steeper than 4 percent. Sheet flow had not formed during the light storm over most of the area, or the rain prints would have been erased. On the few relatively steep parts, however, the crisscross pattern had newly formed, indicating that sheet flow had occurred locally and that its occurrence had depended at least partly on slope gradient.

Sheet erosion and deposition probably do not occur at all, even with torrential rain, on an extraordinarily flat ridge crest plunging at about a 2.5-percent slope gradient between Cerro de Canicjuata and Cerro de Corucjuata. During and immediately after a heavy storm the water-soaked surface ash on the ridge crest was so soft and slushy that one sank 2.5 centimeters into it while walking. The bases of some of the dead trees in the area were surrounded by pools of standing water. A few of these overflowed slightly and sent rills outward for a meter or two. The large volume of rain water sank into the uncrusted ash without forming sheet flow because the slope gradient was so low, and, for the same reason, rill channels were not initiated even from the tree-trunk pools.

Where the surface of the ash is swept clean by rapid sheet flow, crusting is seen, as on slopes of high gradient. On less steep surfaces where there is either no flow or flow with some sheet deposition, either no crust forms or any crust which may have formed initially is buried.

There is no precise boundary line between areas of sheet wash and areas of rill or channel erosion, sheet wash (including the effects of raindrop splashes) occurring on the interfluves in a channeled zone (fig. 35). Areas of sheet wash are progressively invaded by headward-eroding gullies with each successive storm.

On the surface of a bench sloping 6 or 7 percent and dissected by widely spaced shallow arroyos, sheet wash—including the effects of raindrop splashes—had deposited much loose material on the broad interfluves but had left crusted surfaces near the edges of the arroyos where the slope steepened locally, as well as on tiny knolls and hummocks on otherwise smooth interfluves and in areas where drainage was locally cut off from up slope. A few of the larger hummocks were so actively sheet-eroded that the bedding in the ash was cut across and exposed much like the cords in a worn automobile tire (fig. 36).

Rates of precipitation that cause the crisscross pattern on more or less uncrusted surfaces of low gradient, like Llano de Huirambosta, cause different phenomena on steeper, crusted slopes, where the water is shed almost as if from a tin roof. After the first few minutes of a

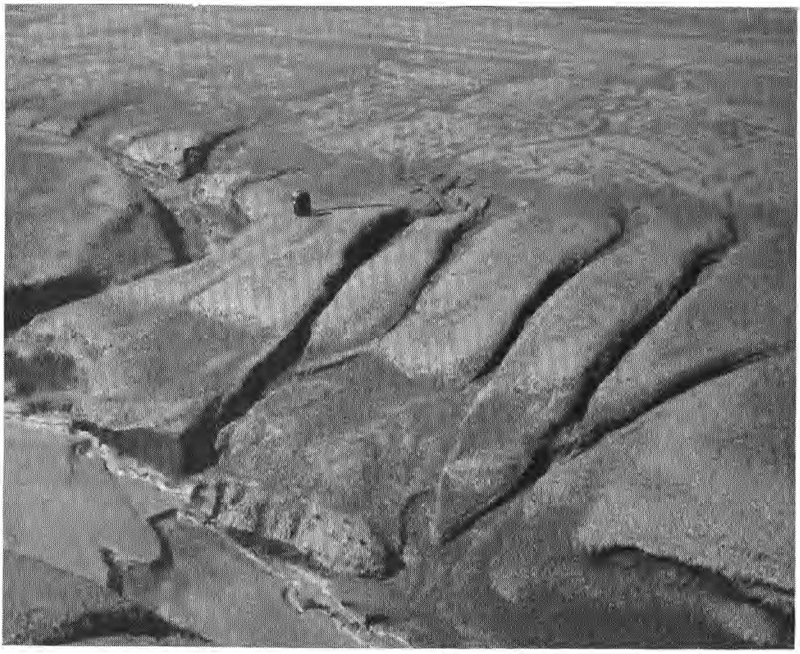


FIGURE 35.—In vicinity of Parícutin. Flat area at top of picture is sheet-eroded, whereas lower, steeper part of same slope is an area of rill erosion.

FIGURE 36.—Peeled onionskin effect caused by active sheet erosion of a hummock on an interfluve near Parícutin.

heavy storm, the crust is covered by a rapidly moving sheet of water which spreads down the slope to the zone of channel cutting. There the water of the sheet may plunge vertically half a meter or more into miniature Grand Canyons, which may be characterized by stepped-down side walls and small buttes of bedded ash. By headward retreat the channels gradually encroach into the zone of sheet flow, although the latter retains its identity on interfluves.

Sheet erosion does not ordinarily occur on the Parícutin cone itself or on the nearby east slope of Cerro de Canicjuata. Except temporarily, just after the eruption of ash containing an unusually high percentage of fine material, the surface of the cone and neighboring slopes is too permeable for surface runoff to occur, even on surfaces sloping 60 percent. Artificial slope steepening can cause local sheet erosion, however; during the 1946 rainy season sheet erosion on a minuscule scale (fig. 37) formed a crust within 4 days on the downhill

FIGURE 37.—Week-old footprints in ash from Parícutin, showing how artificially steepened slopes cause crusting of the ash on the downhill side of the print.

edges of footprints made on the uncrusted east slope of Cerro de Canicjuata. Slope gradients of the tiny areas of crust thus formed ranged from 100 to 150 percent as compared with 60 percent for relatively undisturbed hillside. At Huirambosta, similar results were seen where footprints were left on a surface sloping only 3 percent.

Where pine needles are present on gentle slopes, their arrangement illustrates how sheet wash has alternately eroded and deposited. Pine-needle bars formed normal to one short slope that dipped at about a 10-percent gradient, and in the same area, but where the slope dipped at a 30-percent gradient, crescent-shaped clusters of needles averaging about 20 centimeters in width had formed. The up-slope edge of each cluster was the convex one.

Sheet flow may result directly from rainfall, as on the upper parts of slopes and on interfluves, or from stream flow, as on alluvial fans. Thus far, only the flow derived directly from rainfall has been described, but the patterns formed by sheet wash on large alluvial fans indicate that the same processes of alternate erosion and deposition may operate where the sheet flow is derived from streams. Along the axis of the fan, the slope components are multiple, and the radial lines of distributaries branch out from the small areas of surficial deposition. One fan 11 meters in diameter, for example, had four foci for radial distributaries. Off the sloping sides of the fan axis, however, there are only two slope components; they account for the characteristic parallelogram pattern found there, as contrasted with the wheel-spoke pattern on the fan axis.

RILL EROSION

SIZE, DENSITY, AND GRADIENT OF RILL CHANNELS

The rills that at times form in conjunction with sheet erosion on a low-gradient surface, as at Huirambosta, may be so shallow that the ephemeral pattern they produce can be destroyed by raindrop impact, renewed sheet flow, or wind drift. The comparatively steep, though much shorter, slopes of dunes, for example, may become channeled more strongly by rills, but a much higher rate of precipitation is required to produce rills on dunes than on other surfaces, for the permeability of dune sand is exceptionally high (fig. 16).

A rill-channeled dune observed near the west edge of Llano Grande had a leeward slope 12 meters long. This slope steepened gradually from the top to a line about two-thirds of the way down, where an abrupt increase in gradient resulted in an angle-of-repose slope to the bottom. About one-third of the way from the crest, rill channels began to appear, and just above the bottom there were six to nine channels per lateral meter, all parallel to each other and none branching. Their depth was almost uniformly 1 centimeter, and their width was 2 to 6 centimeters (fig. 38).

These channels, ending at the foot of the slopes, were a result of initial erosion of a newly constructed surface, from which running water did not remove a uniform layer of mantle, as is typical of sheet erosion, but instead was confined to channels and removed material

FIGURE 38.—Rill channels in dune ash near Parícutin, as seen after eolian deposition has started to eras them.

from them. The surfaces of the Llano Grande dunes appeared to be very uniform in longitudinal section, but a small degree of undulation parallel to the slope must have caused the depth of sheet flow to vary enough laterally across a slope for concentrated flow to erode rill channels in the sags. The principle of initial drainage development has been described by R. E. Horton.[48]

Between two benches near Sinámichu there is an ash-mantled slope 40 meters long that has a gradient of 40 percent; the flow of rain water over it is augmented somewhat from the upper bench. In 1946 parallel, uniformly spaced rill channels striated it for a distance of 50 meters or more, measured at right angles to the slope. Each channel was about 30 centimeters wide and 30 centimeters deep, and each was spaced 4 or 5 meters from the others. Interfluves between the main rill channels were still striated with the remains of small initial channels, much like those of the rill-channeled dunes at Llano Grande, that were being obliterated by rain impact, cross grading or lateral planation, and wind drift. This slope was in a more advanced stage of youthful erosion than were the rilled dunes, for the main rills had been enlarged at the expense of the smaller ones.

[48] Horton, R. E., Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology: Geol. Soc. America Bull., vol. 56, p. 332, 1945.

Rill-channel formation, like sheet erosion, depends on the length and steepness of a slope and the resistance of the surface to erosion. The point on a slope where rill erosion begins may become progressively higher, for some rills erode headward with each heavy rain. Where downcutting is greatest, headward retreat is most effective; hence the thickness of the easily cut ash mantle influences the distance across a crest between opposite rill heads.

On the old cone of Sicuín, where the total thickness of ash from Parícutin was only 63 centimeters in September 1946, the crest of the ridge between opposite rill heads was 7 to 10 meters wide. On old cones of comparable slope length, but where the ash has been found to be from 2 to 5 meters thick, the width of the ridge crest ranged from 10 centimeters to 1 meter in 1946 and was commonly only about 20 centimeters (fig. 33). Typically, the slopes drop about 2 meters vertically within a distance of 7 meters on either side of the crest of a crater rim before the slope gradient becomes 60 percent, which is standard for the sides of local cinder cones.

The rill-channel heads along the rims of craters mantled with 2 to 5 meters of ash from Parícutin were spaced about five to the meter in 1946. Each of these rill heads was an amphitheater about 7 centimeters wide with nearly vertical head walls about 2 centimeters high. At a distance of 7 meters down slope from the crests of the deeply ash-mantled cones, cross grading and coalescing of the rill channels had resulted in channels 0.5 meter to 2 meters deep, about 1 meter wide, and with nearly vertical walls. The interfluves were from 1 meter to 2 meters wide at this distance down slope; at distances greater than 50 meters from the crests interfluve widths averaged about 3 meters.

The point on a slope where rill erosion ceases and redeposition begins is not entirely related to a particular slope gradient. If the rills carry capacity loads of sediment, this point may be merely where the slope gradient decreases. Rills often dissect their own miniature fans when they carry light loads. At the bases of a large number of angle-of-repose slopes, deposition by the rills was observed in 1946 to begin at a gradient of 13 to 25 percent.

EFFECT OF TREE TRUNKS ON RILL EROSION

It is something of an anomaly that trees should actually initiate erosion rather than retard it, yet this happens in the Parícutin mantle where dead trunks are still standing. The rain water that runs down these trunks excavates small moats around them (fig. 39), and the overflow initiates rill erosion if the slope gradient is sufficient to carry the water away. For example, on a long slope with a 60-percent gradient a dead pine 35 centimeters in diameter had a moat 20 centimeters wide around it; the overflow formed a rill channel that was 20

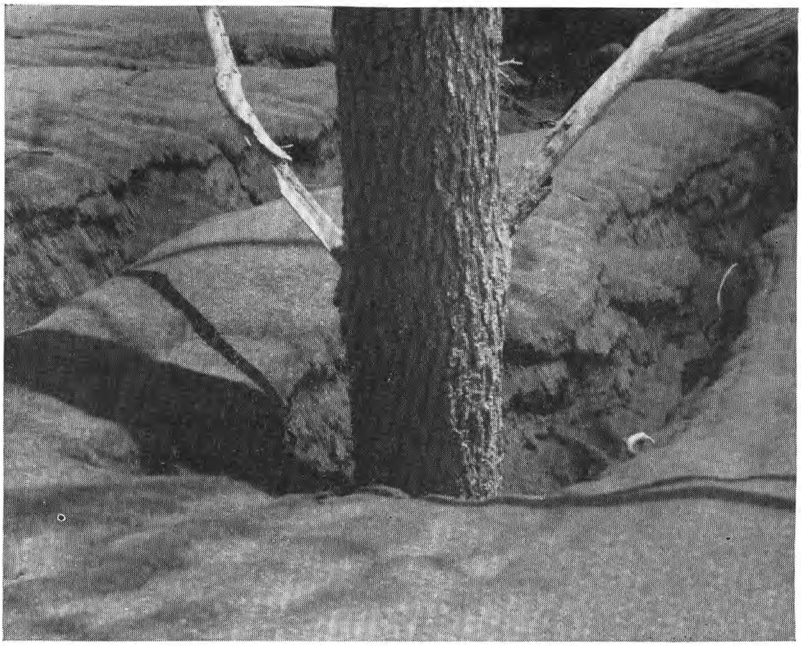


FIGURE 39.—Rill erosion initiated in the Parícutin area by rain water running down a tree trunk.

centimeters wide and 13 centimeters deep at a point 1 meter down slope from the tree. On another slope having the same gradient a dead oak 1 meter in diameter formed a rill channel 1.3 meters wide and 1.5 meters deep at a point 1 meter down slope. Many tree moats become partly filled by material carried down slope by sheet flow and deposited against the uphill face of the trunk, and slope steepening around the edge of a moat not uncommonly causes headward retreat of the rill channel to a point far up slope from the tree.

On the surface of a relatively undissected cone, the tree-initiated rill channels continue their independent courses down the slope except where they find other trees directly in their paths. A rill whose flow is augmented in this manner cuts a larger channel than those that follow independent courses all the way to the bottom of the slope and, at a later stage, captures some of the others by cross grading. Each tree, although supplying water, is in itself a barrier to rill passage, however, so that the rill is diverted slightly to one side, forming bends that disrupt the parallel pattern. When the main rill channels become much larger and may be considered stream channels, their courses through areas of dead forest are often controlled by trees.

South and southeast of Zirosto is a series of long, parallel, convex-topped ridges separated by deep, northward-trending barrancas. Some of the crests of these ridges are barren, as they were cultivated or provided pasturage before the eruption. On each ridge the tree line is somewhat below the crest, where the slope gradient abruptly steepens. The barren area above the tree line has no well-defined rill channels but only faint patterns like those formed where sheet erosion and deposition occur simultaneously. Immediately below the timber line, rill channels are abundant. Thus the forested area is rill-eroded and the barren area either uneroded or sheet-eroded.

The much greater steepness of the wooded slopes accounts in some degree for the accelerated erosion. At one place, however, a broad wedge of clearing was observed to extend 12 meters farther down the steepening slope than the tree line on either side. In this wedgelike clearing no rill channels had formed, although the wooded slopes on either side at the same steepness were deeply scarred by tree-initiated rill channels.

RILL MUDFLOWS ON THE PARICUTIN CONE

The coarse ash on the sides of the cone and on the nearby slopes of Cerro de Canicjuata usually is too permeable to initiate surface runoff. Runoff occurs even there, however, during brief periods after the eruption of exceptionally fine ash, but the water in the rills is soon so reduced by percolation that only enough remains to lubricate mass movement in the form of mudflows. Before Las Pirámides were completely buried by lava early in 1947, rill mudflows formed on their slopes also.

On September 18, 1946, a new eruption had deposited 1.5 to 2 millimeters of fine ash over the cone. A heavy fall of rain followed, and on the south slumped block of the cone the newly deposited surface was cut by rill channels about 5 centimeters wide and 5 centimeters deep, spaced at 2-meter intervals, each terminating in a small mudflow. In places the accumulation of rain water around scattered bombs and in their impact craters had much the same effect as that caused by dead trees. Rill mudflows were initiated that were larger than those resulting only from sheet flow on an undisturbed surface (fig. 40). The usual eruption of coarse material the next day obliterated all traces of water erosion on the cone.

On November 11, 1946, an even thicker layer of fine material was deposited on the cone; a heavy rain followed, and again the ephemeral and rather rare evidence of water erosion was visible. About one-fifth of the circumference of the cone on the northeast flank was streaked with mudflows. Relatively thick alluvial fans built entirely of these flows appeared laterally, at 3-meter intervals, around this side of the cone. Much of the material moved by the mudflows consisted of large lapilli and bomb fragments as much as 5 centimeters in diameter. The mudflow furrows above the fans were from 30 to 60 centimeters wide and 10 to 20 centimeters deep. The interfluves

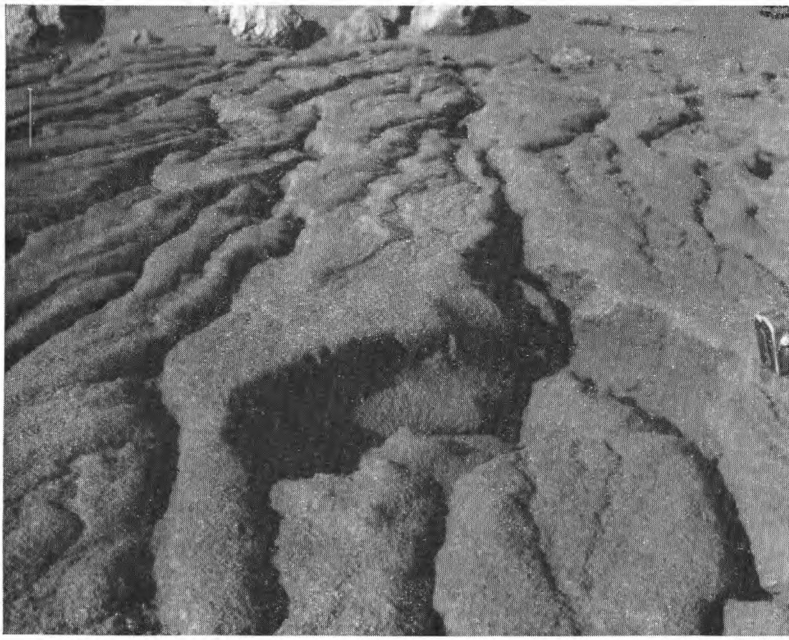


FIGURE 40.—View looking down slope at rill channels in an area near Parícutin pitted with bomb-impact craters.

were densely dissected by rill channels, the average width and depth being 2 to 5 centimeters and the lateral spacing from 10 to 20 centimeters. The courses were quite sinuous, owing to the obstructions formed by bomb fragments. The fine surface layer was 5 millimeters thick, and the size distribution of the particles in this layer showed a peak of 41 percent for the coarse part (grains larger than 0.42 millimeter in diameter) of the sample, indicating that although the material was finer than that usually found on the cone, it was coarser than the average ash found farther away from the volcano.

On the same day the zone of rill mudflows was observed to end abruptly toward the east flank of the cone. There the surface was much coarser grained than on the northeast side. The base of the cone was littered with hundreds of bombs as large as 0.8 meter in diameter. These bombs had evidently swept the surface clean of its new fine material as they rolled down the cone, leaving it too permeable for surface runoff to occur. That fine material had been deposited there, however, was evident from its presence on top of the lava just far enough beyond the east and southeast base of the cone to have escaped complete removal by the rolling bombs. The undisturbed ash mantle over the lava away from the base of the cone was dissected by rill channels and streaked by mudflows.

DESCRIPTION OF TWO AREAS OF SHEET AND RILL EROSION AND REDEPOSITION

During September 1946, a detailed study and map were made of a part of Llano Grande where the effect of sheet and rill erosion could be particularly well observed. This map is presented in plate 2. It will be noted that a large part of the area mapped was covered by debris deposited by sheet flow and that rill channels were abundant. In the following explanation of certain features shown on the map, the letters used in the text refer to the areas indicated by the encircled letters on the map.

The steep slope (B) along the north edge of the map is the only wooded part of the area, except for the scattered trees and maguey plants indicated separately, and the only part where the ash surface is crusted, except for narrow strips at the very edges of the principal channels down slope. Above this wooded slope is an open bench (A) about 150 meters wide, from which two systems of braided rill channels about 100 meters apart spill off down the slope. None of these rill channels is continuous across the upper bench, but sheet wash undoubtedly feeds the channels from above. Gullies down this steep slope (B), of which only the major ones are shown, on an average are 3 meters apart laterally, measure about half a meter wide, and are cut through to the preexisting surface. They do not extend down the whole slope length (C), except where fed directly from the bench above.

Outwash from the steep slope has caused material to be deposited over the surface indicated by shading (D). This consists principally of clumps of pine needles but also of twigs as much as 30 centimeters long, oak leaves, pebbles up to 5 centimeters in diameter, crab apples, and pine cones, in that order of abundance. Near the lower tips (G) of the outwash area, none of the deposited twigs are more than 15 centimeters long, nor are the pebbles there greater than 1.5 centimeters in diameter, but at the very base of the steep slope in the northwest part of the area, twigs are as much as 1 meter long and deposited rocks are as much as 20 centimeters in diameter. The unshaded area (E) is not littered with debris.

The sites of over a hundred ash-thickness measurements are shown on the map, and the thickness at each is given in centimeters. All the gently sloping part of Llano Grande had cornstalks still projecting through the ash, indicating that the terrain was furrowed at the time the ash began to cover it. These furrows account for a difference of 5 to 10 centimeters in the thickness of the ash. The true thickness of aerially deposited ash over this area probably averaged 46 or 47 centimeters. The thinner mantle on the steepest slope shows that sheet erosion has removed an average of about 30 percent of the ash, whereas the thicker mantle at the foot of the same slope shows that material redeposited as a result of sheet and rill erosion higher up slope has augmented the original ash deposit by 30 to 50 percent.

At various places on the map the depth of some of the principal drainage channels is given in centimeters, as well as the sections that are eroded to or into the preexisting soil. Between the discontinuous segments of rill channels shown on the map, there are some braided rill channels less than 1 centimeter deep (F). In the southwest corner of the area, several small mudflows are shown (K), which have an average width of 30 to 50 centimeters and furrow walls 2 centimeters high. They form the principal material making up the alluvial fan at the mouth of a deep channel (L). A still larger channel (M) continues about 150 meters beyond the limit of the area mapped.

Wind-deposited ash amounting to half again as much as the thickness of the original ash mantle covers a part of the area to the east (H). Some of the eastern slope of the area is steep enough (J) for channeling, but the rain that falls directly on the surface is not enough to initiate rills and almost no sheet flow is supplied from up slope.

A topographic map of another area, part of Lomas de Capânguito, was prepared and is shown in plate 3. At this place the slopes are steeper than over most of the Llano Grande area, and at the upper end a dug ditch (F) cuts off all sheet flow from above. As before, the letters used in the following description refer to areas indicated by encircled letters on the map. Sheet wash has caused pine needles and a few twigs and pebbles to be deposited in areas shown by shading. Some of the surface is crusted (C), but other parts are not (A). The unshaded areas (B) are free from sheet-wash debris and crust. In the flat area between the steeper slopes and the lava, broad discontinuous channels (E) not over 10 centimeters deep were eroded by flood waters debouching from a large arroyo (D) in lacustrine deposits formed behind a lava block.

CHANNEL EROSION

CHANNEL EROSION AND THE EROSION CYCLE

It is convenient in explaining the nature of the channeling that is taking place near Parícutin to consider the existence of a small-scale and comparatively rapid dissection cycle in the ash mantle itself. The long cycle through which the preexisting land forms have been passing, except for the direct effect of the old topography on erosion of the ash, is best disregarded for this purpose.

The initial stage, early youth, is described in the pages on rill erosion (pp. 80–87). In the next stage, youth, stream piracy is common and the uniformity of the parallel drainage pattern is destroyed by complex branching. Noticeable changes in stream coalescing and bifurcation take place with each heavy rain. Except for the material removed uniformly by sheet erosion, however, the interfluves still represent the original surface on the aerially deposited ash.

In the third stage, maturity, the interfluves on the slopes of old cones, for example, have lost their smooth constructional surface. In plan they look like oak leaves, the stems of which point uphill (fig. 41), with observed widths varying from as much as 1.5 meters to

FIGURE 41.—Breached crater of a youthful cone southwest of Parícutin, where ash is 2.5 meters thick showing oak-leaf faceting of interfluves on far slope.

30 centimeters and less. The rills formed seek constantly to spill off to one side or the other where the interfluves are narrow, tending to erode them still more deeply.

The fourth, or late mature, stage of dissection is characterized by increasingly narrow interfluves as more and more triangular facets, broad-based downhill and pointed uphill, become isolated from each other at the narrow parts of the oak-leaf pattern (fig. 42). These facets are a miniature manifestation of the planezes described by C. A. Cotton.[49]

The fifth stage, old age, is reached when the facets or planezes are removed by lateral cutting, accompanied by the lowering of the sharp interfluve crests and the development of wide barrancas in the ash.

The sixth or final stage might be considered the period when the last remnants of the ash mantle are being stripped from the slopes.

[49] Cotton, C. A., Volcanoes as landscape forms, pp. 365-367, Christchurch, New Zealand, 1944.

FIGURE 42.—Lower end of interfluve in Parícutin area nearly isolated from upper part by erosion.

The rate at which these successive stages develop depends largely on (1) the length and gradient of the slope, (2) the thickness and particle size of the ash mantle, (3) the density of distribution of the tree trunks, and (4) the rate of deposition of new ash. Because of local variations in these conditions, and because of the occasional reconstruction of some surfaces by newly deposited or redeposited ash, all the stages of dissection may be observed simultaneously in the region. The thickness of the original ash mantle is of course the most important factor in determining whether the full dissection cycle will operate at any one place. Where the ash is less than a meter thick, the channels are widened so rapidly because of the erosion resistivity of the soil floors existing before the eruption that the cycle passes directly from the stage of youth to that of old age.

PROPERTIES OF CHANNELS

The courses of initial, consequent stream channels are controlled by the direction of slope of the surface in which the channels are eroded; on their descent down the hillside, the channels will reflect any change in the direction of slope. Thus the drainage pattern of broad-topped, plunging ridges may be one of curved lines, whose only straight segments will be where the direction of slope is constant (fig. 43). Typical examples of such a pattern characterize the long, nearly flat topped spurs that descend northward from the crest of Cerros de Tancítaro.

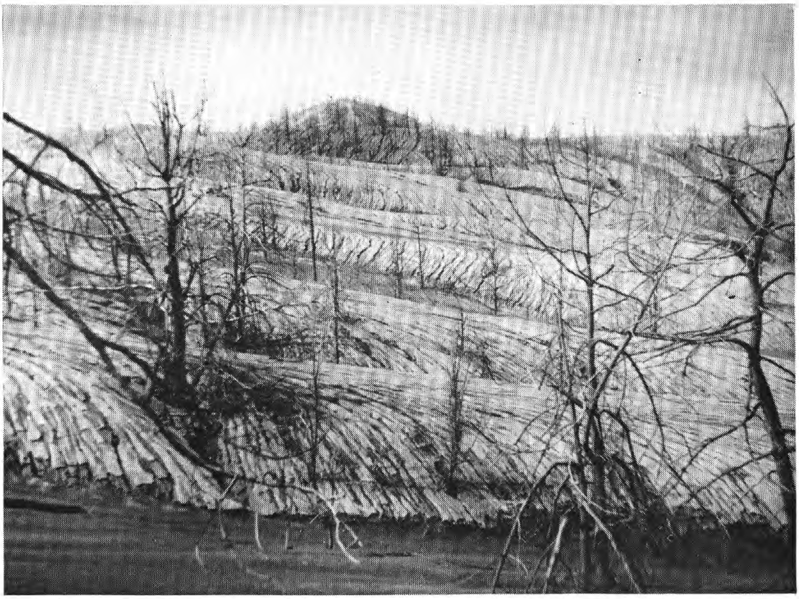


FIGURE 43.—Series of parallel ridges in Parícutin area from which stream channels curve off to either side in response to slope direction.

The channels that initially trend along the plunging crests of these ridges descend to one side or the other in great curves where the ridges become narrow or slightly convex. Where the ridges are asymmetric, headward retreat of the channels on the steeper side results in the capture of the upper, ridge-top segments of some of the channels that curve off to the other side.

This type of piracy occurs on all ash-mantled ridges that have enough gradient in a longitudinal direction to initiate crestline channeling, and new captures may be observed after every heavy storm. At one place the long ridge forming the divide between Arroyo de Corucjuata and the arroyo that drains the west base of Cerro de Canicjuata was found to be of knife-edge thinness. The channel was 60 centimeters deep on one side and 140 centimeters deep on the other; the distance from midstream to midstream through the divide was only 165 centimeters. During a single heavy rain, the deeper channel, draining steeply into the Arroyo de Corucjuata, eroded through this divide and captured, not only the 60-centimeter channel, draining less steeply into the other arroyo, but also another channel at a still greater lateral distance across the slope.

In a broad area of low slope gradient near Huirambosta, a meandering stream channel eroded wholly within the ash mantle was seen in 1946. Within a distance of 200 meters down this 5-percent slope, the stream channel had 13 meanders; its width averaged 2 meters, it was about 1 meter deep, and the width of the meander zone averaged 6 meters. Excess water from a bench above supplied this meandering stream. There were no other channels for at least 100 meters on either side.

Lava flows predating the volcano are expressed in the bench-and-cliff topography on either slope of the valley of San Juan Parangaricutiro. Drainage channels in the ash, penetrating into the soil mantle, are greatly changed at the breaks of slope. All but the largest channels are lost in their own areas of deposition at the upper edges of the benches, and the few channels that continue across the benches show a progressive decrease in their depth from a maximum of several meters almost to zero. Near the brink of the benches these main channels are typically broad, shallow, and braided, but their flow is concentrated in narrow, deep, straight channels on descending a steep slope to the next bench below.

Lava flows from Parícutin have blocked old channels; the new ones cut at their edges are described on pages 31–34.

The boundary-line ditches excavated by hand in areas where rock is scarce have a striking effect on channel development and arrangement. Usually in straight lines down the slopes, they were already eroded to a depth of about 1.5 meters and a width of 1 meter before the eruption, which gave them a start over the consequent streams that later formed on either side on top of the ash mantle. These new consequent streams are becoming tributary to the ditches, resulting in the enlarging, deepening, and unifying of the drainage channels on many hillsides. Similar to the influence of the dug ditches is that of old logging roads.

In cross section the channels eroded in the ash are typically box-shaped, but the ratio of width to depth is quite variable, depending in large part on the thickness of the ash mantle. A channel is much more rapidly eroded in coarse than in fine ash, and consequently its floor is generally composed of a fine-grained bed. After a channel has been widened by lateral cutting on top of a resistant bed, the floor may be breached and a step formed that migrates rapidly up the channel. The floor then continues to be eroded down through the coarse material to the next fine-grained bed, when another period of lateral cutting begins. Theoretically this process should result in a stepped-down effect along the sides of the channel, but on fairly well graded slopes the lateral cutting is so efficient that all the steps that may have formed above are usually removed and the walls are generally nearly vertical. Along channels of very low slope gradient, however, the stepped-down effect remains in the walls because the slower-moving flood flow has a smaller lateral cutting force.

The fine beds provide support for the channel walls, as the coarse ash alone would collapse, and in many places they are etched out in miniature cliffs. Vertical channel walls more than 2 or 3 meters high are rarely formed in the mantle of ash from Parícutin. Along deeper channels they occur generally above piles of unconsolidated debris sloping downward less steeply to the bed of the stream. Very close to the cone, where fine-grained beds are few, channel walls sloping about 45° are common and vertical walls are absent or, if present, very short-lived.

Although the ratio of width to depth in different channels is quite variable, the channels larger than rill size that are eroded entirely in ash are ordinarily about as wide as they are deep. If, however, the channel reaches the underlying soil, which is more resistant to erosion than any bed of ash, this ratio becomes quite different, although the section is still boxlike (fig. 44). At many such places

FIGURE 44.—Channel eroded in ash from Parícutin but with floor of preexisting soil.

no further downcutting is accomplished, and the channel becomes wider and wider until it coalesces with its nearest neighbor, resulting in the complete stripping away of the interfluve. After the channel has become several times as wide as it is deep, a narrow inner channel may be eroded into the preexisting soil, producing a box-within-a-box profile (fig. 45).

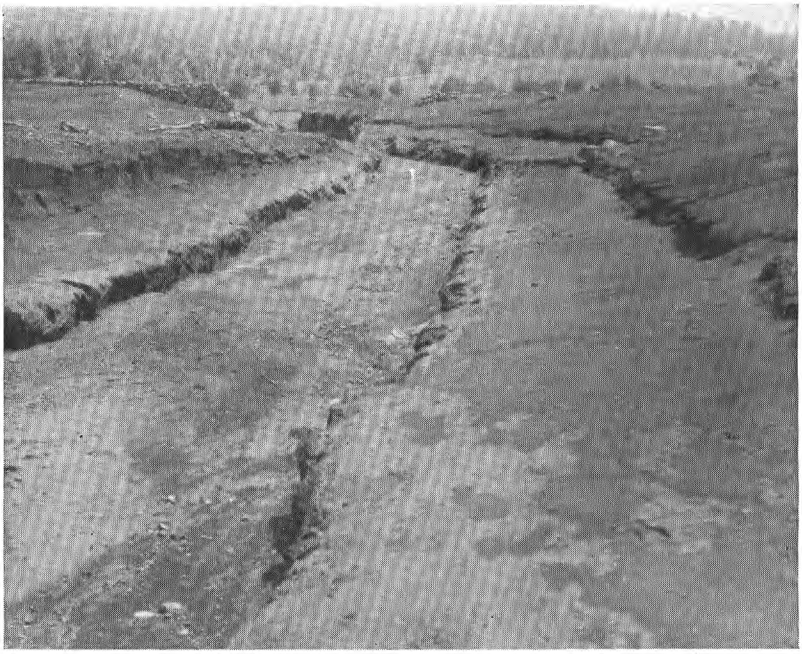


FIGURE 45.—Box-within-a-box gully near Parícutin, with intermediate benches formed on preexisting soil.

Obstructions such as logs or stone fences across the stream channel also produce abnormal channel widening.

Local steepening at the heads of streams accelerates erosion, which causes the channels to retreat headward. Within the ash mantle, this process is the same as that of channel deepening and proceeds by the upstream migration of steps and falls in the channel bed. Headward retreat amounting to 8 or 10 meters occurred in one channel 2 meters deep during 15 minutes of heavy rain.

The cohesiveness of fine-grained beds in the ash mantle is illustrated not only by the vertical walls of channels but also by the rare formation of tunnels. Where such features form, the surface beds are so resistant that, though breached, they hold up in the form of natural bridges and tunnel roofs while the streams that penetrated them erode the underlying beds. One such example was a side channel, 1 meter wide and 1 meter deep, which flowed under a roof in the last 1.5 meters before entering the main channel (fig. 46).

Ultimately the new channels become tributary to the main stream channels that were present before the eruption. About half these old channels are blocked and diverted by lava flows and therefore are filled with redeposited ash where they debouch into lava-impounded lakes, but most of the others empty into the deep, narrow gorges of the Río de Itzícuaro and its tributaries.

FIGURE 46.—Covered channel in Parícutin area formed by rapid erosion of coarse underlying beds.

PROPERTIES OF INTERFLUVES

On steep slopes where the ash mantle is more than 3 meters thick, a multiple isoceles-triangle pattern of facets—planezes in miniature—may appear, formed by the convergence and junction of channels over different parts of the slope (fig. 41). This effect is characteristic of the late mature stage of the erosion cycle in the ash. The facets were best developed in 1946 on the youthful cone of Loma Larga, where the ash was about 5 meters thick and the former surface was probably the original constructional surface of the cone. Facets are also very marked on the thickly ash-covered old lava flows in the same area. Gradients of slopes showing good development of facets range from 30 to 75 percent; facet widths vary from 60 centimeters to 5.5 meters at the base; and the height of an average facet, measured along the slope, equals the basal width.

On slopes gentler than those on which facets form, the profiles across the interfluves become convex as the dissection stage passes from youth toward maturity. Their convex surfaces usually slope gently toward the edges of the channels on either side, and sheet erosion has cut across and exposed the ash bedding (fig. 47). In some places parts of slightly convex interfluves, isolated as their narrow divides are eroded, remain standing in the form of miniature buttes or mesas. The general appearance of an area in which the interfluves are thus eroded is much like that of mesa-canyon terrain

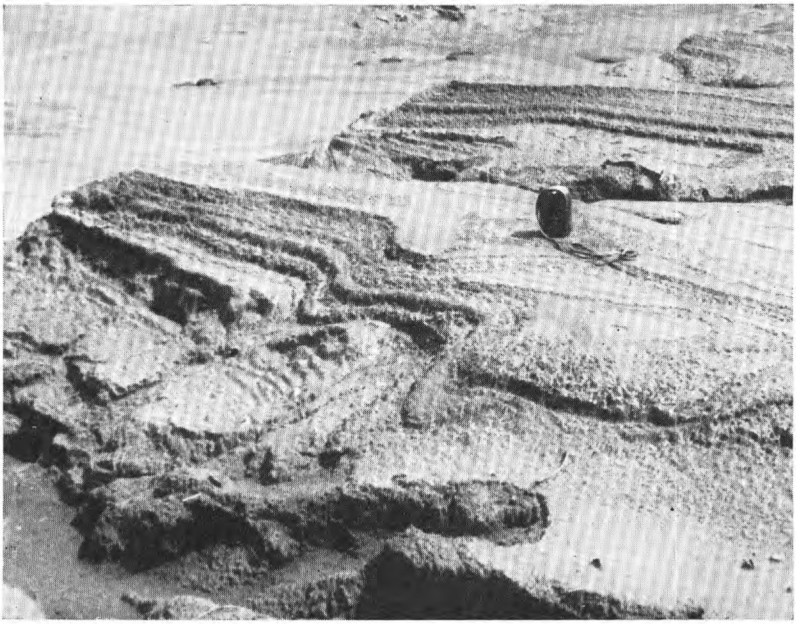


FIGURE 47.—Exposure of beds of ash from Parícutin along the bank of a stream.

as seen from a great altitude. Near the edges of the low-gradient interfluves the upper beds of ash are partly peeled away by raindrop splash and sheet erosion and in some places may be striated by rill channels. A miniature stepped-down effect is produced. Differential erosion of the coarse and fine beds tends to produce miniature terraces bordering many interfluves, but where the storm flow through the channels moves with sufficient force to cause caving and lateral cutting, these terraces are destroyed.

RATE OF CHANNEL CUTTING

The fastest rate of channel cutting observed in the ash-covered terrain around Parícutin was in a barranca that cut across the Casita Canicjuata ridge on September 20, 1946. During a storm on that day, lava-impounded flood waters were suddenly released across the ridge and eroded a barranca several hundred meters long, 7 or 8 meters wide, and as much as 5.8 meters deep. On October 11 this barranca was 20 meters wide and as much as 12.4 meters deep. It had been cut, not only through the immensely thick ash mantle, but as much as 1.6 meters into the underlying soil (fig. 7). Blocks up to 0.8 meter long were washed from the Parícutin lava field and transported through the new channel as far as 175 meters beyond the base of the Casita Canicjuata ridge. By October 18, when a new lava flow quickly filled the gully and effectively stopped further cutting, the width of the barranca had reached 30 meters (fig. 8).

The barranca just described was exceptional, but many other examples could be cited of relatively rapid channel cutting in the ash mantle during heavy storms. The few permanent streams present in the region have eroded into the preexisting soils and underlying rocks, in which channel cutting is very slow compared to the rate of cutting in the new ash.

STORM DISCHARGE AND TRANSPORTATION OF SEDIMENT

The brief torrential rains that occur almost daily from June to October in the Parícutin region swell the many arroyos of all sizes and the few small permanent streams up to and in excess of their channel capacities. Storm waters become laden to the limit of their carrying power with easily removed ash particles and larger objects such as boulders and logs.

Movements of ash-laden water upstream against flood currents, like the "sand waves" described by R. C. Pierce in the San Juan River, Utah,[50] were measured on several streams. In general, the waves were either straight or slightly convex downstream in plan, and they extended across the middle one-fourth or one-third of the channel at right angles to the direction of flow. At Llano Grande, in a flood-swollen stream 10 meters wide and about 45 centimeters deep, flowing at approximately 2 meters per second, several sand waves—each about 30 centimeters high and following each other at 4- or 5-meter intervals—retreated upstream at an average speed of 1.5 meters per minute. In a freshet 15 meters wide and 85 centimeters deep, flowing at 2 meters per second in the large arroyo at the base of Lomas de Capânguito, a sand wave 1 meter high was observed to move upstream 1 meter in 8 seconds; of several other sand waves occuring shortly afterward, none lasted more than 3 or 4 seconds.

The sand waves are surface expressions of the antidune movement of bed load described by G. K. Gilbert. The downstream slopes of the antidunes are eroded, and their upstream slopes receive deposit.[51] Antidunes in streams of the Parícutin region appear only near the peak of a flood, if at all, and they last only a few minutes. The flood surfaces are nearly always smooth.

Table 11 shows the results of observations of stream flow made during the 1946 rainy season. Correlations can probably be made experimentally between stream gradient, channel depth, velocity, and load of suspended matter, but from field observations this could not be done with any degree of certainty. Other factors difficult to express quantitatively, such as the width and length of the water-

[50] Pierce, R. C., The measurement of silt-laden streams: U. S. Geol. Survey Water-Supply Paper 400-C, p. 42, 1916.

[51] Gilbert, G. K., The transportation of débris by running water: U. S. Geol. Survey Prof. Paper 86, p. 31, 1914.

TABLE 11.—*Observations of stream flow near Parícutin*

Place of observation	Gradient of stream bed (percent)	Low stage: Width (meters)	Low stage: Depth (meters)	Low stage: Velocity (meters per second)	Low stage: Volume (cubic meters per second)	Low stage: Percent of height of solids column to height of sample	High stage: Width (meters)	High stage: Depth (meters)	High stage: Velocity (meters per second)	High stage: Volume (cubic meters per second)	High stage: Percent of height of solids column to height of sample
Arroyo between Capánguito and Tipacua	1.5	--	--	--	--	--	15.0	0.85	2.0	25.5	12.4
Small stream northwest of Cuezeño [1]	6.9	--	--	--	--	--	1.0	.10	1.4	.14	3.6
Small stream just east of Cuezeño [1]	3.5	--	--	--	--	--	1.0	.05	1.3	.06	8.5
Arroyo de Urengo,[1] north of Cuezeño	2.2	3.0	0.1	1.2	[2] 0.36	4.4	5.7	1.1	3.1	19.4	14.9
Arroyo de Urengo,[1] Llano Grande	.43	--	--	--	--	--	6.5	.08	1.2	.65	9.6
Arroyo de Urengo,[1] Llano Grande	.43	--	--	--	--	--	11.0	.60	1.8	11.9	--
Arroyo de Huirambosta, just above junction with Arroyo de Corucjuata	1.4	--	--	--	--	--	1.0	.20	1.7	.34	37.8 (W-30) [3]
Río de Itzícuaro, just below junction of Arroyo de Huirambosta with Arroyo de Corucjuata	3.8	--	--	--	--	--	5.0	.50	2.2	5.5	72.2 (W-29) [3]
Arroyo de Corucjuata, just above junction with Arroyo de Huirambosta	3.1	--	--	--	--	--	5.0	.3	--	--	88.4 (W-31) [3]
Arroyo de Corucjuata, alluvial fan at Sinámichu	8.6	--	--	--	--	--	2.0	.50	1.4	1.4	58.8 (W-7) [3]
Barranca de Huachángueran	1.8	1.3	.04	.75	.04	2.2	4.0	1.0	2.4	9.6	57.9 (W-22) [3]
Río de Itzícuaro, opposite Zirosto	2.3	1.6	.06	.95	.10	1.0	8.0	.75	3.1	12.4	78.8 (W-11) [3]
	2.3	5.5	.50	2.0	[2] 5.5						
Barranca de Queréndaro	1.5	.25	.35	.54	.05	1.1	1.8	.60	1.7	1.6	30.1 (W-10) [3]
Río de Itzícuaro, 1 km. east of San Francisco	3.2	3.8	.18	.84	.57	2.1 (W-15) [3]	4.3	.35	1.5	2.3	57.0 (W-12) [3]
Río de Itzícuaro, bridge of Imbarácuaro	.20	5.5	.25	1.2	1.6	--	--	--	--	--	--
Río de Itzícuaro, south of Los Reyes [4]	--	15.0	.50	1.0	[2] 7.5	4.4	18.0	.80	--	--	1.1

[1] Arroyo normally dry.
[2] Observation made during period of waning flood.
[3] Number of sample taken for testing.
[4] Observations for the Río de Itzícuaro south of Los Reyes made at 2 places by Celedonio Gutiérrez.

course upstream from the point of observation, the quantity of cave-in and landslide material available, the presence of obstructions in the channel, and the degree to which the underlying soil is exposed, all affect the loads transported.

The load of a stream may be expressed as the relation of the height of the column of solid particles settling from a sample in a cylindrical flask to the total height of the column of water plus solids. The porosities of these sediments average about 33 percent; hence one-third must be deducted from the resulting figure to obtain the true percentage by volume. As shown in table 11, Arroyo de Urengo, north of Cuezeño, with a velocity of 3.1 meters per second, carried only 15 percent solids, whereas the Río de Itzícuaro, with a comparable depth, volume, gradient, and velocity, carried 79 percent. There are two reasons for this great difference in load: (1) Urengo flows through wooded terrain where a carpet of pine needles retards erosion and where all the tributary channels have cut down to the comparatively resistant preexisting soil, but the Río de Itzícuaro drains the devastated zone where there is almost no living vegetation and where most of the tributary channels are still being cut through new ash. (2) Urengo's flood was leveling off, whereas the Río de Itzícuaro's was rising when these samples were taken.

The great influence of depth and volume on stream velocity is illustrated by comparing Arroyo de Corucjuata with Barranca de Huachángueran. Corucjuata, with more than four times the gradient of Huachángueran, had a little over half its velocity when the observations were made. The explanation is that Huachángueran carried seven times the volume of Corucjuata.

The Río de Itzícuaro south of Los Reyes carried low percentages of solids at the time of observation, in spite of the large volume of water, because the stream had been depositing its load on a broad flood plain upstream. There the gradient of the stream bed was only 1.4 percent, which is less than half that of the same stream at San Francisco, where, with less volume, 57 percent solids was carried.

Histograms of particle-size percentages in sediments from stream-flow samples show that the particle size, like the percentage of solids carried, is much smaller for stream flow of small volume than for large floods. Three samples collected from the Río de Itzícuaro, at the same place but at different times, show that the 2-percent sediment load carried by normal flow (sample W–15) contained 93 percent silt-and-clay size and that the 57-percent sediment load carried by flood flow (sample W–12) contained 17 percent silt-and-clay size. The water-deposited ash from Parícutin along the bank (sample C–12) contained only 3 percent of this fine fraction (fig. 48). These three samples also indicate the sorting that results from sedimentation.

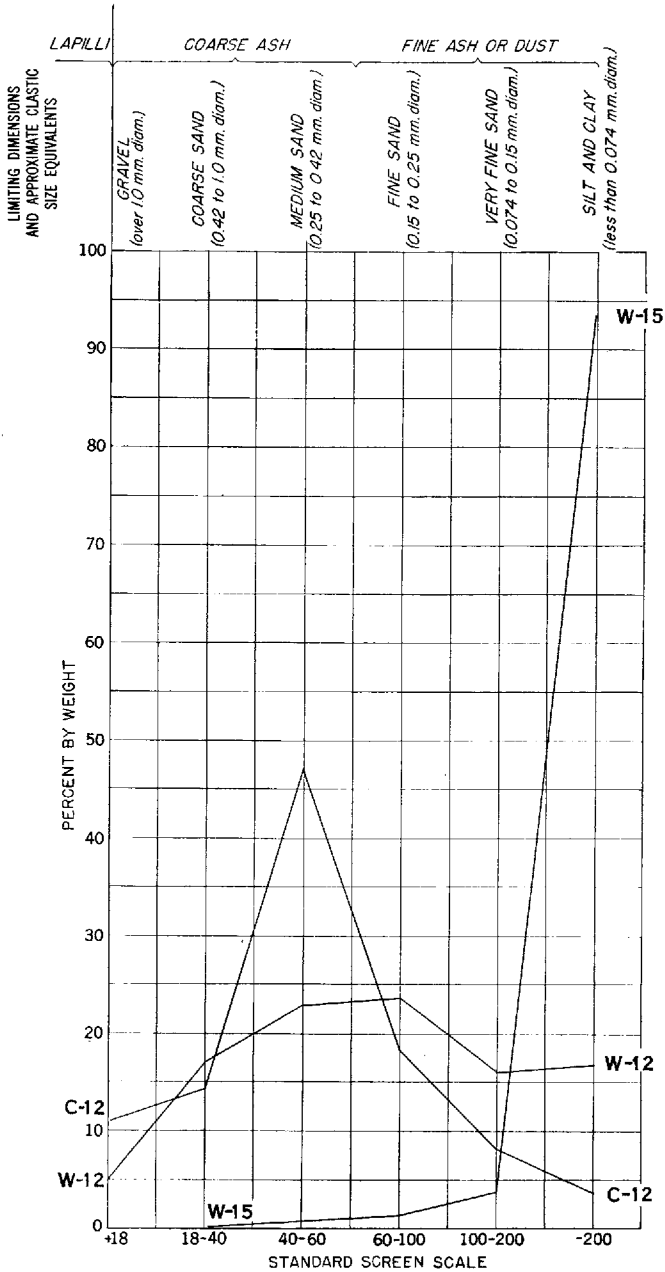


FIGURE 48.—Graph showing size distribution of particles in solid fraction of two stream-flow samples and one water-deposited sample from the Río de Itzícuaro, west of Parícutin.

The size distribution of the particles in the solid fraction of four stream-flow samples collected near Zirosto is shown graphically in figure 49. This and the preceding graph (fig. 48) indicate that the percentage of silt-and-clay size in the solid fraction of the samples is roughly in inverse proportion to the percentages of the heights of the columns of solids to the total heights of the samples. For example, the sample that contained 49 percent silt-and-clay size in the solid fraction was 30 percent solids (W–10); that with 41 percent fine material, 39 percent solids (W–9); that with 35 percent fine material, 52 percent solids (W–8); and that with 17 percent fine material, 79 percent solids (W–11). This relationship for these and other samples of stream flow is shown graphically in figure 50.

Figures 51 and 52 show that the finest stream sediments contain much higher percentages of silt-and-clay size than the finest ash beds sampled and that the coarsest stream sediments contain much lower percentages of gravel than the coarsest ash beds. Within the area studied, channel-fill deposits contain a much greater proportion of medium particles than most of the aerially deposited ash, because the finest fractions are carried downstream and out of the region.

About half the water-borne solids—virtually all those not trapped by the Parícutin lava field—are eventually carried by the westward-flowing Río de Itzícuaro through a series of narrow gorges to the broad flood plain at Los Reyes, 20 kilometers distant by air line from the lower end of the lava field and 900 meters lower in altitude. About two-thirds of the way down, the river passes through Imbarácuaro, the narrowest and deepest of all its gorges. At a place where the Imbarácuaro gorge is 22 meters deep and only 6 to 9 meters wide, a plainly seen high-water mark is 12 meters above the bottom. A plane-table map was made to determine the area of the channel section up to the high-water mark, and the velocity of the permanent stream with its normal volume of water was measured by means of floating sticks. The velocity was found to be 70 meters per minute and the volume 1.6 cubic meters per second.

The Río de Itzícuaro hydroelectric plant of the Compañía Eléctrica Morelia is near the bottom of a wider, cliff-lined gorge about 3 kilometers below Imbarácuaro. The floor of the plant is 4.8 meters above the bed of the river, which has an average gradient of 1.8 percent. Before the volcano erupted, no floods reached the floor of the plant, but on June 12, 1943, flood waters laden with ash from the new volcano were 40 centimeters deep inside the plant; on August 11, more than 1 meter deep; and on August 29, 2.69 meters deep. Estimates of flood velocity on August 29 made by plant employees varied from 15 to 24 kilometers per hour. The lower figure, which is equivalent to about 4 meters per second—a figure certainly not too high—with an estimated

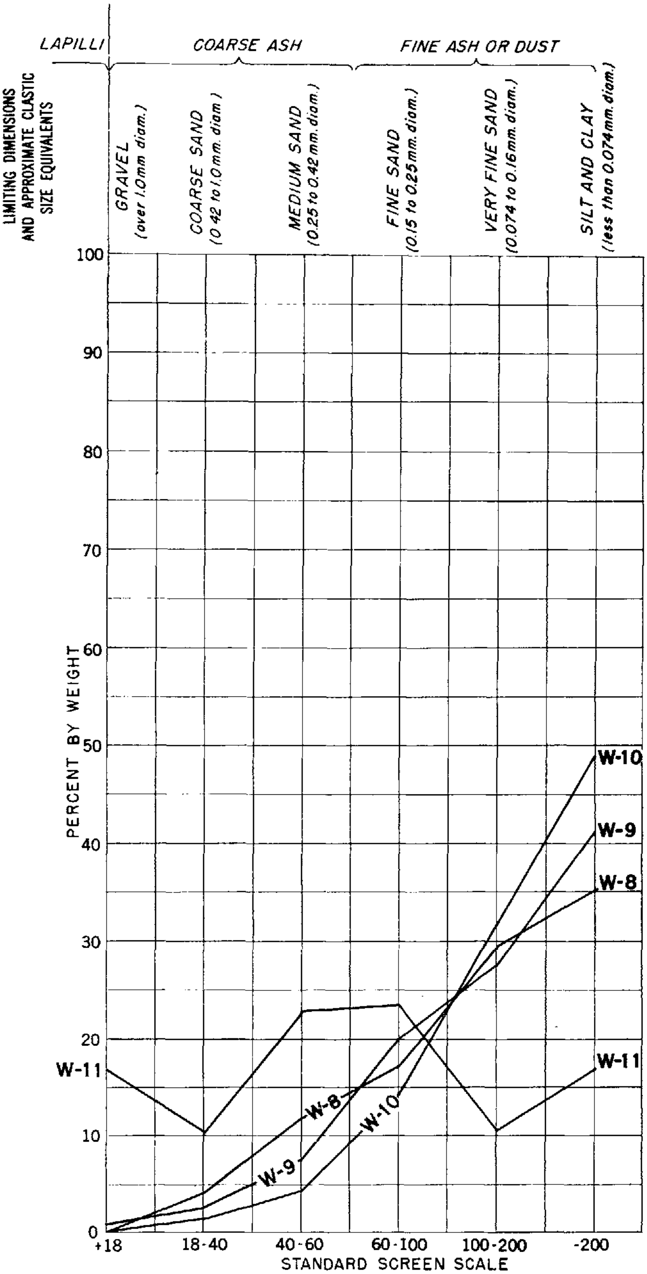


FIGURE 49.—Graph showing size distribution of particles in solid fraction of four stream-flow sample collected near Zirosto, in the vicinity of Parícutin.

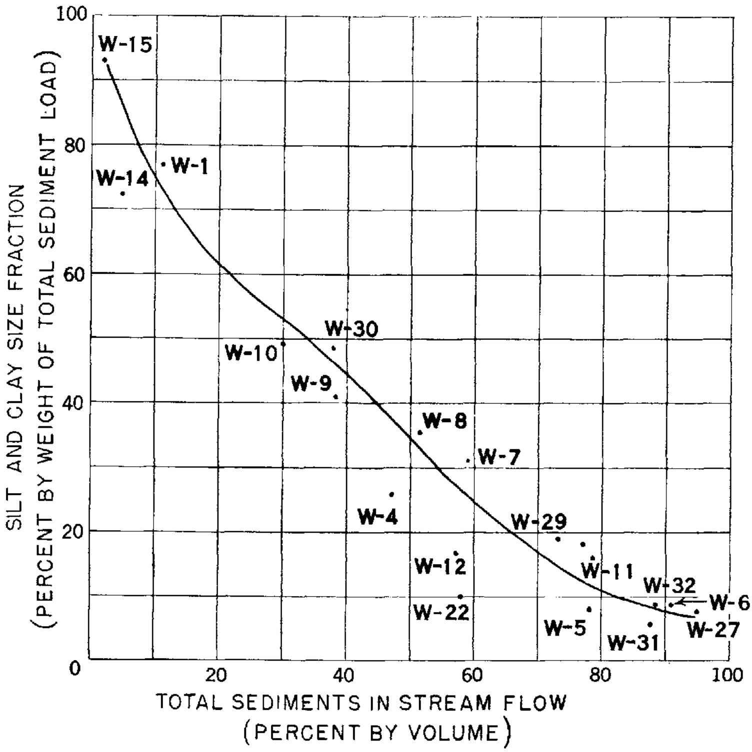


FIGURE 50.—Graph showing relation between total sediment load and percentage of silt-and-clay size in solid fraction of stream-flow samples taken in Parícutin area.

cross-section area of 240 square meters gives a flood volume of approximately 950 cubic meters per second, of which 80 percent was reported to be sediment. Following the largest flood, the turbines were not uncovered until September 5; then, on September 6, a new flood rose to a height of 1.28 meters above the floor, depositing sediment that closed the plant until September 28. During the succeeding dry season, engineers straightened the river channel somewhat and made it 6 meters wider for distances of 150 meters both upstream and downstream, and the floods of 1944–46 did no damage to the plant.

About 0.008 cubic kilometer of ash was deposited by water over the principal part of the Los Reyes flood plain. If all the sediments carried by the August 29 flood had been deposited here, it would have required 17½ minutes during the peak flow to bring in this volume of material, but some of the sediments were of course laid down at other places and the extreme peak stage lasted only a few minutes. The material transported during the extremely high stage, if continued for 1 hour, is equivalent in volume to a layer 1 centimeter thick over the entire surface of the watershed. As no large tributaries enter the

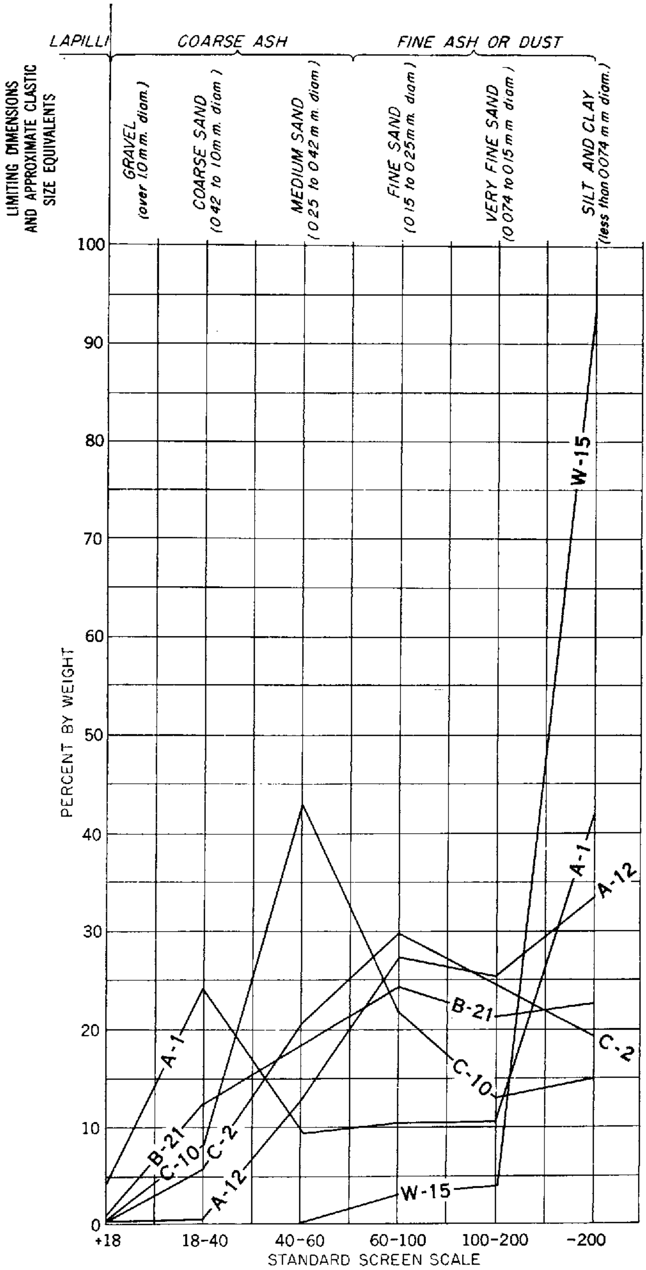


FIGURE 51.—Graph showing size distribution of particles in samples of the finest-grained ash beds and stream-flow solids taken in the Parícutin area.

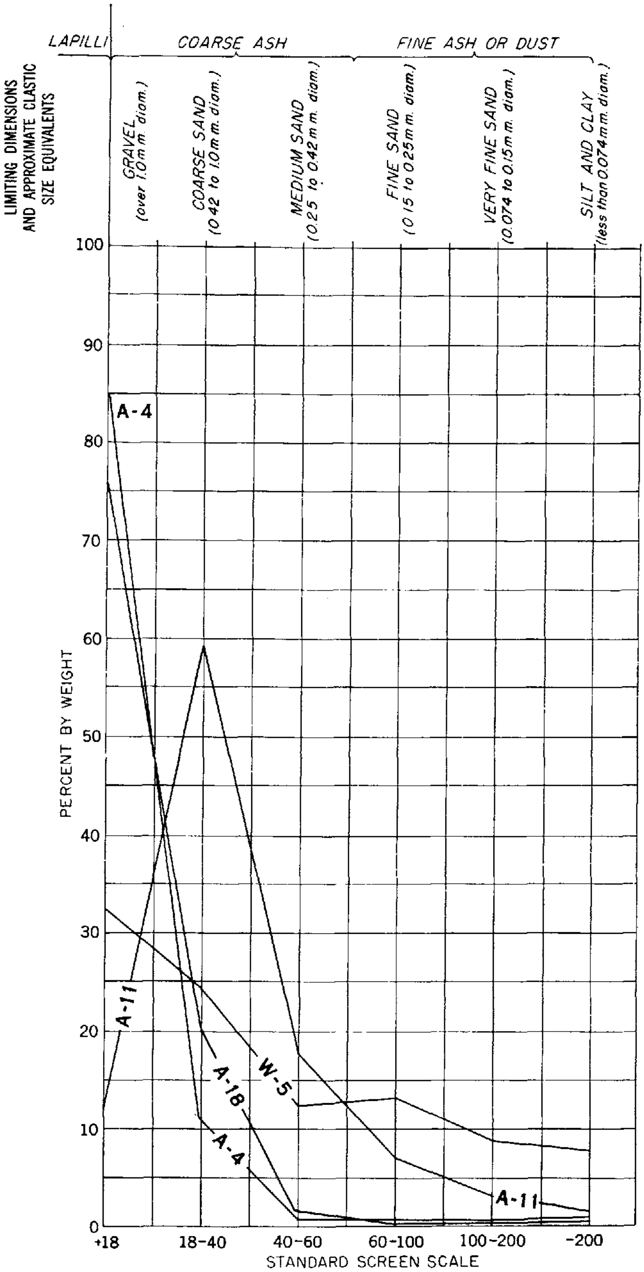


FIGURE 52.—Graph showing size distribution of particles in samples of the coarsest-grained ash beds and stream-flow solids taken in the Paricutin area.

Río de Itzícuaro between Imbarácuaro and the hydroelectric plant, nearly all this flood of 950 cubic meters per second must have passed through the Imbarácuaro gorge, where the area of the channel section up to the high-water mark is approximately 95 square meters. At the time of the peak flow on August 29, 1943, the velocity of this closely confined current through the gorge must therefore have been 10 meters per second.

At the Planta de San Pedro, a hydroelectric plant of the Compañía Eléctrica Morelia on the normally spring-fed Río de Cupatitzio in Uruapan, 14 floods were recorded for 1943, 35 for 1944, 42 for 1945, and 27 for 1946. Only a very few floods in the Río de Cupatitzio occurred on the same days as floods on the Río de Itzícuaro, illustrating the characteristically local nature of the rains that fall in the region. The floods of July 3 and September 18, 1943, at Planta de San Pedro were extraordinarily large, both reaching a peak flow of about 150 cubic meters per second, but the records show that only six floods reached volumes as high as 100 cubic meters per second in 1944, one in 1945, and one in 1946. The normal flow of the Río de Cupatitzio used to range from 8.8 to 9 cubic meters per second, but in 1935–36 it began to decrease and continued to diminish gradually to about 7 cubic meters per second (at minimum flow) during April and May and about 8 cubic meters per second throughout the rest of 1946, except when augmented by the normally dry Barranca del Zirimo west of Uruapan or the normally dry Barranca de San Lorenzo north of Uruapan.

The Planta de San Pedro receives its water supply from the river itself; hence its turbines are affected to a greater extent by flood sediments than those of the Planta de Itzícuaro, which, although located on the river bank, receive a permanent supply of 8 cubic meters per second directly from La Majada spring, located on the rim of the river gorge high above the highest flood levels. Before the eruption, the largest floods in the Río de Cupatitzio had volumes of 50 to 60 cubic meters per second with little sediment; even when the gates were left open, the intake canals of the Planta de San Pedro never silted up. Floods since the eruption have at times carried so much sediment, however, that on the few occasions when the gates were open the canals filled with silt up to the top of their banks. During the first few months after the eruption, the floods from both west and north were very heavily laden with sediment; later, when heavy rain fell to the west, toward the volcano, the intake gates were kept closed, but when the rain fell to the north, the floods were so much cleaner that the gates could generally be left open.

It is increased sediment load that accounts for the greater volume of floods since the eruption. Samples taken of various 1943 floods at

859358—50——8

Uruapan showed sediment loads of 50 to 75 percent; if, for example, a flood of 100 cubic meters per second contains a 75-percent load, expressed as the relation of the height of the column of solid particles settling from a sample in a cylindrical flask to the total height of the column of water plus solids, and the porosity of the sediment is 33 percent, the actual volume of water flowing in the Río de Cupatitzio is about 50 cubic meters per second. This is comparable to the size of floods before the eruption.

In the absence of discharge records for the Río de Itzícuaro and precipitation records for its watershed, we must rely on indirect evidence that the rate of runoff was probably not increased as a result of the ash mantle from Parícutin. Fifteen percent sediment characterized heavily loaded flood samples taken at Planta de Itzícuaro before 1943. The difference between this load and the most heavily ash-charged 1943 loads is about 60 percent, which with the reduction for sediment porosity gives 40 percent more total flood volume represented by a given amount of water in 1943 than before 1943. Measurements of the river channel, allowing for the widening done by engineers during the 1943–44 dry season, show that it had a capacity for floods somewhat larger than 60 percent of the peak volume of the catastrophic flood of August 29, 1943, and it is said that the limit of channel capacity was nearly reached more than once before the eruption. It appears, then, that runoff from the ash-mantled terrain was no more rapid in 1943 than from the same area before the eruption. After 1943, the flood discharge of the Río de Itzícuaro was, of course, reduced by lava blocking.

TRANSPORTATION OF BOULDERS AND LOGS

Close examination of streams that move over ash from Parícutin at normal rates of flow, when there is little suspended matter, reveals that at places where the water flows over large boulders the under edge of the comparatively clear current is dark-colored. Unsuspended particles apparently roll and bounce along the channel floor. The same effect, though on a much larger scale, is produced during flood stage, when large boulders are similarly transported. For example, a flood with a velocity of 2.4 meters per second, carrying 58 percent suspended solids, was seen to be moving rocks as large as 70 centimeters in diameter at a stream gradient of 1.8 percent. The rocks moved at about the same speed as the largest floating logs accompanying them. The depth of the current was at least 1 meter, which was greater than the diameter of the largest boulders, yet the rocks appeared to move mostly at the surface. The specific gravity of the silt-laden flood water was found to be 1.93, and that of the boulders was probably between 2.65 and 2.95. The illusion of actual floating must have been created by the frequent saltation, or bobbing to the surface, of the boulders as they rolled and slid along the uneven channel floor.

Many boulders up to 2 meters in diameter occur within and on top of alluvial ash deposits; these must have been transported by high-density floodwaters. The increase in observed peak-flood loads from approximately 16 percent (in areas where only material antedating the volcano is eroded) to 80 percent (in areas where ash from Parícutin is being eroded) represents an increase in the specific gravity of the flood waters from 1.25 to 2.08. The result is that moving boulders bob more readily to the surface during freshets and hence move faster and farther than before 1943.

Floods occasionally carry, for a few meters, large blocks of ash derived from fresh cave-ins along the stream bank. These blocks appear to break up as they sink to the bottom of the stream.

The force of a freshet that descended the west face of Cerro de Curupichu is illustrated by the logs, driftwood, and ash cast upon the lava field blocking this gully 70 meters beyond the foot of the hill. Logs up to 15 centimeters in diameter and several meters long were deposited on the lava at levels as high as 5 meters above the foot of the hill (fig. 53).

FIGURE 53.—Flood debris thrown against the edge of the San Juan lava flow, from Parícutin, by a torrent descending Cerro de Curupichu.

REDEPOSITION BY WATER

Water-deposited sediments may be divided into two separate groups: (1) those dropped on slopes and stream beds as the velocity decreases and (2) those deposited from standing water. Group 1 includes alluvial fans, flood plains (including unusually large alluvial fans), channel fills, and sheet deposits (including terraces on hillsides). Group 2 includes lake deposits of all kinds.

ALLUVIAL FANS

Cone-shaped alluvial deposits form at the bases of all the hills in the area mantled by ash from Parícutin. The size and slope gradient of a fan depend on (1) the length, gradient, and number of tributaries of the gully above it; (2) the microtopography of the slope upon which the fan is built; (3) the presence of mudflows; (4) the intensity of storms; (5) the obstruction of the toe of the fan by lava or adjacent slopes; and (6) the length of time since the fan started to form. In the ash from Parícutin, channels with a gradient of 60 percent and a length of about 100 meters build fans from 5 to 10 meters long; with a length of about 200 meters, they build fans from 10 to 20 meters long. Still longer gullies have fans in proportion to their length and the number of channels tributary to them; Arroyo de Corucjuata is about 2.5 kilometers long above its alluvial fan, which is 600 meters long. The average slope gradient of the head of a fan in the ash from Parícutin is about 15 percent and, for the toe, about 10 percent. Extremes are 25 percent, as on mudflow fans near the volcano, and 6 percent, as on the large alluvial fan at the mouth of Arroyo de Corucjuata.

Fan deposits are sorted and, except for mudflows, cross-bedded. Lapilli washed out of coarse beds are concentrated at the heads of many fans near the volcano. Gullies eroded into the underlying rock have supplied floodwaters with boulders sometimes 2 meters in diameter, which are deposited on the surfaces of fans built largely of ash from Parícutin. At the south base of Cerro de Tzintzungo, weathered scoria as large as 10 centimeters in diameter are carried out onto the fans. In the vicinity of Angahuan, thin sheets of fine soil partly cover the ash. As the toes of the fans advance, and as the fans are dissected and redeposited, cross bedding within the fan section becomes complex. At the northwest base of Cerro de Curupichu, unweathered ash fans have extended themselves outward over soil-filmed lake deposits, causing cross bedding and interbedding of weathered material with unweathered ash.

FLOOD PLAINS

The floodwaters of the Río de Itzícuaro spread out, lose their velocity, and drop their load of solids on the Los Reyes flood plain.

Plate 4 shows the part of the plain that was most affected by floods before the lava blocked the drainage at Huirambosta. With a watershed including all the area within the 50-centimeter isopach of plate 1, the Río de Itzícuaro was supplied with enormous quantities of ash in 1943, and much of the sediment carried by the floodwaters was redeposited in an area of about 4 square kilometers between El Huatarillo, Presa de Los Limones, and the town of Los Reyes. The gradient of the river bed decreases from 2.2 percent in the gorge above El Huatarillo to 1.2 percent on the plain at El Aguacate.

Evidence of the large volume of ash-charged silt brought down by the Río de Itzícuaro was still visible in 1946, when about 1 square kilometer of flood plain just north of El Aguacate was covered to an average depth of half a meter by redeposited ash from Parícutin. A maximum thickness of 1.5 meters was seen in the river bank, and throughout the 4 square kilometers originally covered by the flood-borne ash, thicknesses of 10 to 20 centimeters were common. A stone boundary fence 60 centimeters high, extending for hundreds of meters across the plain, was buried to the top by ash deposited on the upstream side. If the average thickness of the ash redeposited on the Los Reyes flood plain by the Río de Itzícuaro during the 1943 floods (which have not been repeated since) was 20 centimeters over an area of 4 square kilometers, the total amount of material redeposited would be 800,000 cubic meters, which is about 0.2 percent of the total volume of ash initially deposited over the Río de Itzícuaro drainage basin above El Huatarillo, or the equivalent of removing 3 millimeters of ash from the surface of this area.

Equally large quantities of ash were redeposited by the Río de Xundan, which drains a large terrain over which ash ranging in thickness from a few centimeters to half a meter had originally been deposited. Descending the northwest flank of Cerros de Tancítaro, the Río de Xundan passes through the town of Peribán and joins the Río de Itzícuaro between El Aguacate and Presa de Los Limones. Over a distance of 8.3 kilometers between Peribán and its mouth, where the average gradient of the Río de Xundan is 3.4 percent, the river silted over about 4 square kilometers of fields. The greatest concentration of large boulders dropped by this river occurs on the outskirts of Peribán, where boulders up to 2 meters in diameter are not uncommon. Many of those that litter the broad area where the Río de Xundan and the Río de Itzícuaro join were brought down by the ash-laden floods of 1943; boulders 20 to 30 centimeters in diameter are common there.

Smaller flood-plain deposits cover the numerous little benches at the north base of Cerros de Tancítaro and the south base of Cerros de Angahuan, where they range in width from about 200 meters to 1 kilometer. Situated at the mouths of steeply inclined gullies, these gently sloping areas receive the heavily laden floods that are funneled out of the mountains. A great reduction in slope and a sudden release from confinement in a gorge immediately cause the torrents to drop the coarsest material, but the rest is carried across and down to lower levels. If the bench is broad enough, some of the remaining boulders and coarsest gravel are deposited near the lower end, but little ash is dropped. Measurements showed that the total ash thickness was never more than a few centimeters greater than the local original thickness.

An example of the bench type of flood plain, where incomplete deposition has resulted only in dropping the coarsest material and carrying most of the load downstream, is Llano del Cantero, 5.5 kilometers south of the cone. At the upper end of this bench, boulders up to 2 meters in diameter and large logs (fig. 54) were deposited on top of

FIGURE 54.—Boulders and logs carried from slopes of Cerros de Tancítaro, south of Parícutin, and deposited on Llano del Cantero by floodwaters.

37 centimeters of ash, which is roughly the thickness of the aerially deposited ash. Five hundred meters downstream, no boulders larger than a meter across were seen, and a couple of hundred meters still farther on, at the lower edge of the bench, only coarse gravel was deposited. For the next 700 or 800 meters the stream is confined in a narrow valley, descending much more steeply until it is finally funneled out onto a broader, flatter flood plain called Llano de Teruto.

Teruto is the largest of the flood plains near Parícutin. For a total length of 2 kilometers, its average grade is only 2 percent. In an area

300 meters below the place where the arroyo from Llano del Cantero debouches onto this plain, most of the remaining flood-borne boulders (up to 1 meter in diameter) and logs are deposited. Before 1946 the arroyo continued to flow from this point toward the lower end of the llano, depositing practically all its sediments and building a broad fan of ash from Parícutin as much as 5 meters thick. The last of the large elements of the stream load were dumped on the fan about 800 meters below the upper end of Llano de Teruto. Subsequently the floods were diverted into a tributary valley, where the smaller sediments were deposited in lake beds (p. 117).

In plate 5, based on plane-table surveys made in April 1945 and September 1946, the increase in the thickness of the water-deposited ash in the vicinity of Cuezeño is shown for a 17-month period that includes most of two rainy seasons. Since the datum was the same, the higher altitudes in 1946 as compared with 1945 are due to ash-depth increment; this was proved by digging some 20 test pits. The deposits are of the flood-plain type and occur a short distance up slope from a lake bed. The bedding of the material on the flood plain is inclined parallel to the slope (1.5 percent). As the lake bed fills with sediments and its level rises, the flood-plain deposits will be covered with nearly horizontal beds.

CHANNEL FILLS

Streams flowing over the easily eroded ash in the area of high relief west of the cone are quickly loaded to capacity. The sediment load is not dropped immediately, when the water reaches the gentler gradients of the Río Itzícuaro and its principal tributaries, because the streams are confined in narrow gorges and maintain their velocity. At places of channel broadening, however, the heavily charged torrents lose substantial parts of their load as the velocity decreases and especially as the volume of the flood lessens. The resultant channel filling, followed by considerable reexcavation during the next storm, produces narrow inner channels bordered by lenses of ash as much as 5 meters thick. These deposits reduce the volume of floods a channel can contain, and overflowing of the banks may occur during heavy storms.

A single storm may cause a reexcavated channel to be partly or completely filled again. Where the arroyos from Corucjuata and Huirambosta join, 5.5 kilometers northwest of the volcano, the level of the stream bed was raised 2.5 meters by the storm of September 20, 1946, when 49 millimeters of precipitation was recorded at Cuezeño. The material deposited was brought down mostly by the stream from Corucjuata. The Huirambosta stream, less vigorous than before lava from Parícutin cut off most of its supply, was dammed; at a point 60 meters upstream the floor was actually 7 centimeters lower than at the junction, a striking example of how the base level of a stream may be raised. Much litter of driftwood and coarse gravel-size material was strewn over the stream floor. At a point 160 meters downstream from the junction, the entire arroyo floor consisted of the surface of an old lava flow, which served as a dam that held back the ash deposited upstream. Before the eruption of Parícutin, when flood-flow sediment loads probably reached a maximum of 16 percent instead of the present (1946) 80 percent, the stream was never sufficiently overloaded to permit such a thickness of material to be deposited in its channel floor above the lava dam.

In an arroyo about 2 kilometers northwest of the volcano, a channel-fill deposit averages about 50 meters in width for a distance of half a kilometer, and judging from the steep slopes on either side (gradient, 50 to 100 percent) and the narrowness of the valley bottom as seen on the preeruption aerial photographs, the thickness must be very great—perhaps up to 25 meters. No complete section has been cut through this fill; only shallow and discontinuous channels were seen. The surface is slightly higher in the middle than at the sides (fig. 55).

Usually the bedding in channel deposits is poorly defined. Over most of the region, floodwaters tend to deposit medium-grained material in the channels, leaving the coarsest particles much closer

FIGURE 55.—Floor of valley below area of landslides near Parícutin. Arroyo bed is filled to great depth by water-deposited ash.

to the place of removal (lapilli on hillside fans, for example) and carrying the finest particles out of the area studied in detail. Figure 48 shows the size distribution of particles in three samples taken from the same place: one of normal stream flow, another of flood flow, and a third of material deposited on the river bank during previous floods. The predominance of medium-sized particles in the river-bank deposit illustrates the type of sorting characteristic of channel-fill deposits. As the ash mantle is gradually stripped, ocher-colored material antedating the volcano becomes more abundant in the stream sediments. Along a watercourse east of Zirosto, a bed of soil 1.5 centimeters thick was deposited on top of 30 or 40 centimeters of water-deposited ash.

SHEET DEPOSITS

The ash deposits at the bases of slopes become thicker as a result of sheet erosion of the interfluves above and fan building at the mouths of channels. Such thickening is most easily recognized where the ash mantle on the slopes above has been completely stripped off and only lenses of ash are left at places where the slope flattens (fig. 56). These lenses may be thicker than the original aerially

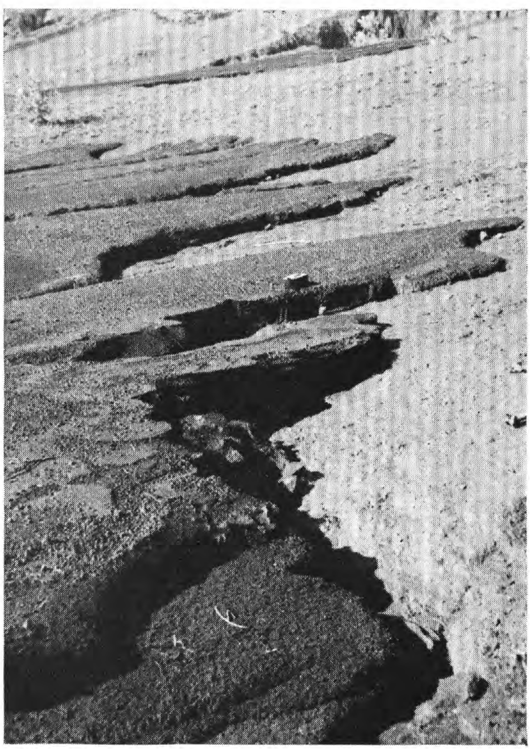


FIGURE 56.—Fingerlike remnants of ash from Parícutin left at the foot of a slope from which the mantle has been stripped.

deposited ash, proving that some of the material was redeposited by water. On the long slopes of Llano de Huirambosta, well out of the path of streams, redeposited material on the uphill side of fallen logs is unmistakable proof of sheet deposition. On slopes of very low gradient, sheet erosion and deposition occur together and leave alternate rill channels and miniature fans (see pp. 75–76).

Rock fences built to separate pastures and fields in the region are usually about 1 meter high by 75 centimeters thick. Where they cross hillsides normal to the slope, they act as check dams and impound the ash that is sheet-eroded from above. Ash has commonly piled to the tops of these fences on the uphill side, but the surface of the terraces thus formed is not horizontal and varies in slope from 6 percent, on hillsides sloping 10 to 20 percent, to 9 percent on hillsides whose slope is about 40 percent. The continuity of these terraces is broken at intervals by gullies that have opened incomplete passageways through the fences.

Against the uphill sides of standing trees and large boulders, the sheet-deposited ash is well bedded in many places. Such deposits are cone-shaped and rimmed by sharp edges eroded by runoff that has passed by on either side.

LAKES IMPOUNDED BY LAVA

The deposits formed in lakes impounded by lava (see pp. 32–33) are very thick on the south edge of the lava field; furthermore, the thickness increases rapidly during each rainy season. Plane-table surveys made 18 months apart in this area show that the level of the cove at the mouth of the arroyo 400 meters south of the Cocjarao triangulation station rose from 2,510 to 2,550 meters above sea level and that the level of the ash fill at the edge of the lava half a kilometer farther east rose from 2,504 to 2,529 meters. Sections through these deposits would show that the ash is interbedded with three or four layers of lava, each about 4 meters thick and with alluvial fans, sheet deposits, and mudflows.

North of the lava field, where the slopes are less steep and the aerially deposited ash is thinner, the lacustrine deposits increase in thickness much more slowly. Three years after the San Juan flow blocked the drainage on the north side of the San Juan valley, the edge of the lava had not yet been buried by redeposited ash except just north of Cerro de Curupichu, where the lava thickness is unusually small (only about 3 meters). At Chórotiro, a pole fence 1 meter high that had been built in the spring of 1946 was half buried by redeposited ash by autumn of the same year.

Since the ash mantle has been removed and some of the underlying soil has been eroded in arroyo channels north of the lava field, an admixture of ash and ocher-colored earlier soil characterizes the redeposited material at Chórotiro and Llano Grande and in other lake beds. As the water recedes, a film of transported soil is left at some places, introducing into the stratigraphic column thin zones of highly weathered material which might someday be falsely interpreted as soil horizons. Fine material, both weathered and unweathered, brought in by successive floods cannot escape as it does where the floods continue downstream; thus all the load is deposited, and the average grain size of the lacustrine deposits is finer than that of channel fills. The graphs in figures 48 and 57 show that an ordinary lake deposit in the Parícutin region contained 55 percent very fine grained sand-size material (sample D–24), whereas a typical channel fill contained only 8 percent (sample C–12).

Lake-deposited sediments of average size distribution do not seem to form contraction cracks as the lake dries up, but where extraordinarily fine material has settled from the water, mud cracks usually form. Mud-crack material forming a bed 3 centimeters thick over coarser material was found to contain 96 percent silt-and-clay-size particles (sample D-23), whereas the underlying material contained only 22 percent silt-and-clay size (sample D-24), as shown graphically in figure 57.

The distance between mud cracks is a function of the thickness of the contracting layer, for the faster this layer dries, the less capacity the blocks have to take up contraction. Thus smaller blocks are formed where the layer is thin. At Chórotiro, the following measurements were made:

Thickness of mud layer (millimeters)	*Distance between mud cracks (centimeters)*
1	3–7
4	6–10
10	15–27
80–100	30–120

The pattern made by mud cracks, although erratic, ordinarily consists of a system of long cracks roughly parallel or concentric to each other, connected by short cracks that break up the intervening strips into irregular blocks (fig. 58). More rarely, cracks form in closed circles that have several hooklike branches curving outward from their circumference. At times, only the long cracks form without the accompanying short transverse cracks, although they may be edged with closed-circle cracks. Some short transverse cracks extend only part way between two long cracks, indicating that there may be different stages of development.

Once lake-bed mud has contracted and cracked, rewetting apparently does not expand the material and close the cracks. On the bottom

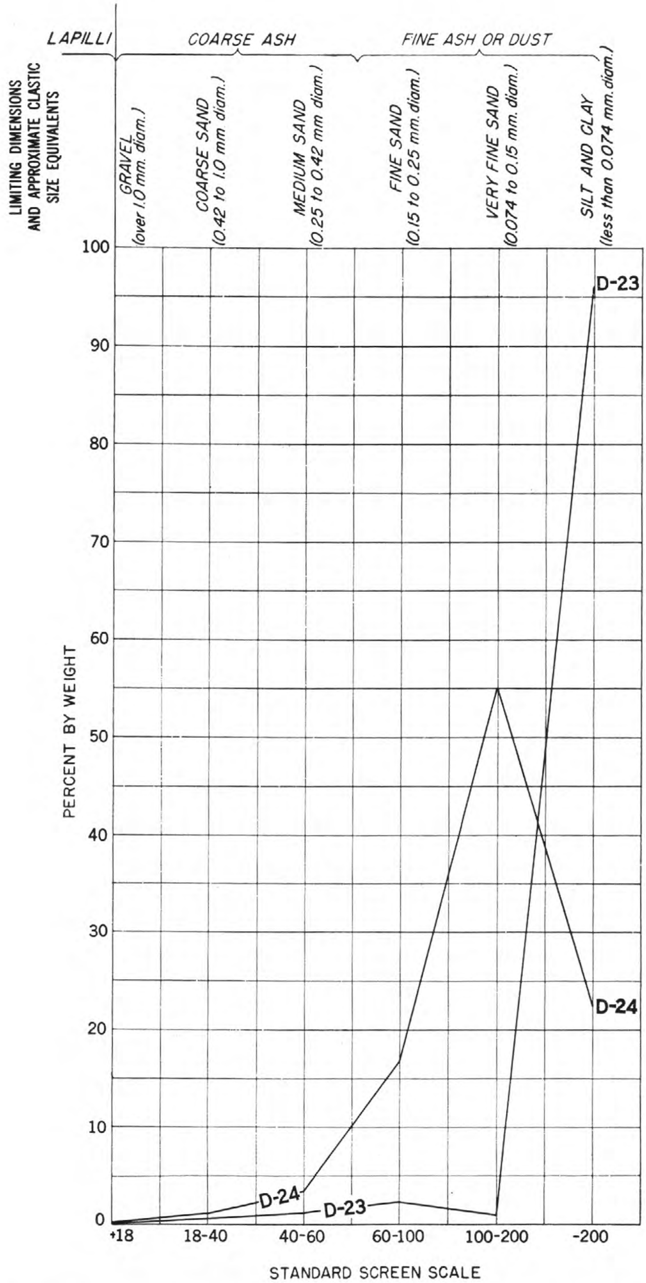


FIGURE 57.—Graph showing size distribution of mud-crack material and noncracking lacustrine material in Parícutin area.

FIGURE 58.—Pattern of mud cracks of the type most commonly seen on lacustrine deposits of ash from Parícutin admixed with preexisting soil.

of a pond of clear, shallow water, the cracks formed during the last dry period appeared intact and as open as ever.

When new cracks form on a surface already cracked, they do not seem to coincide with their predecessors, although the orientation of the main longitudinal cracks remains roughly the same (fig. 59). The new film of sediment may cement the old cracks so firmly that the surrounding material can break apart more easily than the healed cracks.

LAKES IMPOUNDED BY ALLUVIAL DAMS

The flood-plain deposit at Llano de Teruto (pp. 110–111) has sealed off the eastern part of the plain and produced a basin. Inasmuch as the floodwaters do not drain out through permeable lava at this place, a large body of water forms and remains there for months during and following the rainy season. On September 23, 1946, this irregular body of water was 300 to 500 meters long by 200 meters wide. In the memory of the oldest inhabitants, no lake had ever formed at this place before the Parícutin eruption. If the alluvial dam at Teruto is not washed away, the sediments deposited in the lake will eventually cover an area about 1 kilometer long by half a kilometer wide to the level of the dam, which was 5 meters higher than the lake in 1946.

FIGURE 59.—Two sets of mud cracks at Chórotiro, near Parícutin, showing how the well-defined newer cracks fail to follow the pattern of the older, filled cracks.

CRATER LAKES

Of the 35 or more craters in an area of 85 square kilometers around Parícutin (pl. 1), only Cutzato, Tzintzungo, and Curitzerán contain bodies of water, and those only at times. Several small craters north of Jarátiro, now buried by lava from Parícutin, formerly held water also. The shape of the area covered by water or mud flats and the position of this area with respect to the sides of the crater are significant in determining the bedding of the material being deposited.

The elliptical floor of Cutzato is 150 to 200 meters wide. On July 12, 1946, the shore of an intermittent lake in this crater was 90 meters out from the foot of a slope 300 meters long leading to the highest point on the rim and only 30 meters out from a slope 100 meters long leading to a lower summit, showing that a greater volume of inclined fan deposits had originated from the longer slope (pl. 6). A 5-meter rise in the level of the lake would cover the entire crater floor with water, although such a large volume of water will probably never accumulate from runoff on such a small watershed. Nevertheless, as the horizontal lake deposits thicken and the overlapping fan deposits encroach on them from all sides, an extremely complex cross bedding is being developed.

In the crater of Tzintzungo, which is about 100 meters wide at the bottom, water stands against the side that has a rim height of only

6 meters. On July 23, 1946, the pond was crescent-shaped, for material derived from a slope beneath a summit 40 meters high on the crater rim had built a fan part way across the floor. The crater is the source of the spring that emerges from the southeast base of Tzintzungo and formerly supplied the town of San Juan Parangaricutiro. (Many of the villages in Michoacán depend on the springs of cinder cones for their water supply.)

The northeast crater of Curitzerán is about 130 meters in diameter at the bottom, and the southeast rim is only 1.5 meters above its floor. Stripping of the ash cover on the inner crater slopes will probably cause the floor to be silted up enough to permit the water to drain out. The lowest part of the crater floor is pear-shaped, with the large end opposite the lowest saddle, the small end near the next-lowest saddle, and the indentations at the foot of two high points on the crater rim.

Water does not stand very long on the floors of these craters. In one of the Jarátiro craters, since destroyed by lava inundation, the area of a pond about 25 meters wide was observed to shrink by half within 3 hours. All the other craters are much farther from Parícutin, and as the ash that was originally deposited over them was finer-grained than at Jarátiro, the lake beds in them are probably less permeable.

WIND EROSION

During the dry-season months (December to May), from about 10 o'clock in the morning until 5 o'clock in the afternoon when the daily winds die down, the atmosphere is so full of ash that local visibility is at times reduced to less than 100 meters. Most of the ash is picked up by winds from the western quadrant, but some is lifted by random whirlwinds or dust devils and a little by winds from the eastern quadrant.

The winnowing action of the dust devils causes enough sorting of the surface ash to leave visible tracks. In places these tracks consist of winnowed ash in zones from 20 centimeters to 2 meters wide, but the smallest dust devils leave only a series of discontinuous circular segments along a wavy line of winnowed surface only 1 centimeter wide.

The following observations were made during the middle of the 1946 rainy season on the second day of an unusual rainless period: Driven by a moderate east wind, twisting wisps of dust whisked westward over Llano de Huanárucua, 7 kilometers north of the cone. They were 10 to 20 centimeters wide and spaced about half a meter apart, some following the slope of the land down faint swales and around tiny hillocks, others seeming not to be influenced by the microtopography. In scattered areas between dry, coarser-grained wind ripples, the ash surface had a thin, fine-grained, noticeably damp crust that in places appeared to have been eroded by the wind, remaining only on minuscule buttes surrounded by deflated areas 1 centimeter deep. On the side of a hollow surrounding a large maguey plant, the crust had been stripped off and the underlying, almost paper-thin ash layers were exposed, some of them overhanging each other by as much as 0.5 centimeter. Twenty-four of these layers could be counted on the side of the hollow, which descended only 10 centimeters in a distance of 80 centimeters (fig. 60).

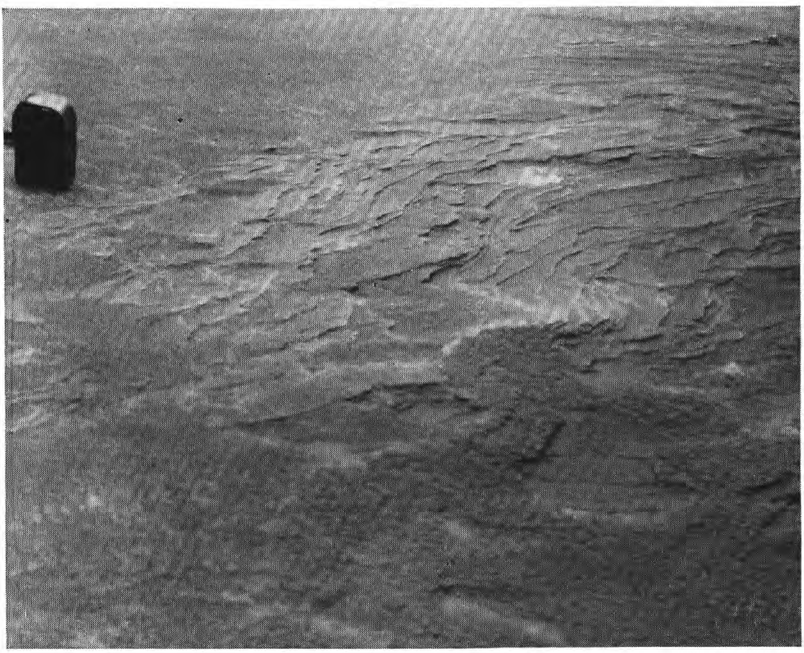


FIGURE 60.—Beds of ash from Parícutin, exposed and partly removed by wind deflation.

A similar effect has been noted in windward-facing, slightly damp arroyo banks, where the wind has etched out the edges of coarse beds and left sharp-tipped flakes of the fine-grained beds projecting outward from the bank. An entirely different effect is sometimes noted in leeward-facing, thoroughly dry banks, where wind-drifted material produces hourglass-shaped cave-ins in which the inverted-cone amphitheater at the top is matched in size and shape by the talus cone at the bottom.

REDEPOSITION BY WIND

The almost complete lack of rain from December to May, together with the strong winds that blow during these months, accounts principally for the building of ripples and dunes. Minor factors are the surficial drying of rain-soaked ash on slopes adjacent to hot lava flows and the direct deposition from an eruption of dry, new ash over the damp surface of older ash. The ripples and dunes range from a few millimeters to 2 or 3 meters in amplitude. They have gently sloping windward faces and steep leeward slopes. Ash particles are blown up the gentle slopes and dropped over the crests.

The difference between sand ripples and dunes is said to be one of size and distribution. W. H. Twenhofel [52] states that the amplitude of most ripples is between 2 and 4 millimeters and the wave length between 5 and 10 centimeters. Ripples form continuous parallel-line or network patterns, whereas dunes occur in groups, each member of which has an amplitude that varies from about 1 meter to many meters.

Ripples in the ash from Parícutin of more or less standard size appear in over-all patterns of both the parallel-line and network variety; those of somewhat larger size occur singly or in clusters; and comparatively large dunes are as much as 3 meters high. The large ripples or small dunes are barchans; that is, they have a crescentic shape, with their horns pointing leeward (fig. 61); or they are

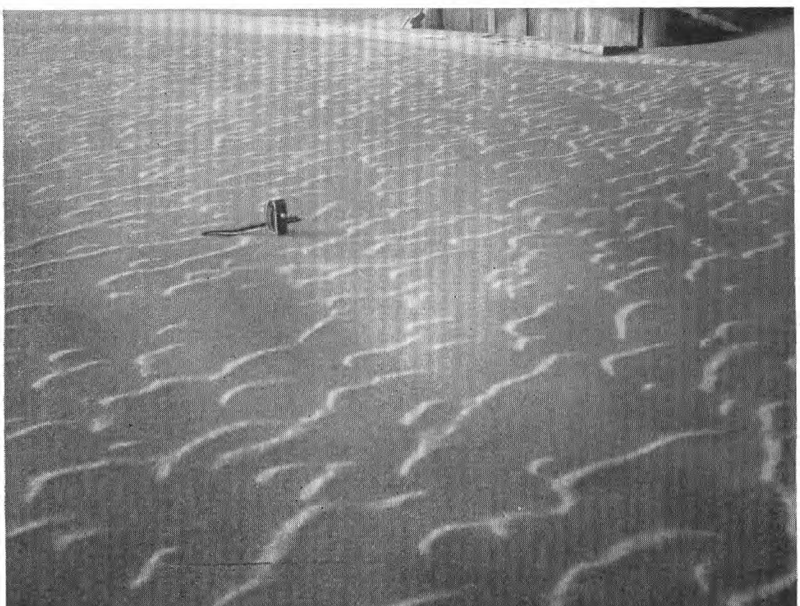


FIGURE 61.—Barchans in miniature at Sinámichu, near Parícutin. The wind forming them blew from left to right.

[52] Twenhofel, W. H., Principles of sedimentation, p. 528, New York, 1939.

elongated across the course of the wind with their irregular lobes pointing leeward (fig. 62). The larger dunes are also of the barchan

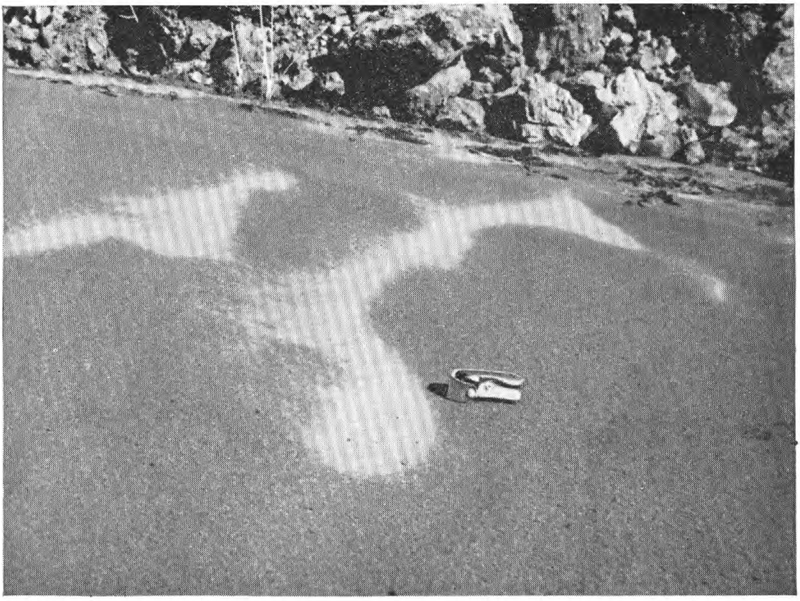


FIGURE 62.—Small dunes in the Parícutin area, elongated across the course of the wind with lobes pointing leeward.

variety, except where modified by obstructions or topographic lows, and their surfaces themselves are rippled.

In small barchan-shaped dunes, the largest particles are just off the crest on the leeward side. The average material in small dunes is larger-grained than the surface ash between them, the graphs in figure 63 showing a particle-size peak of 57 percent coarse particles in the dune material (sample A–15) as compared with a peak of 37 percent fine particles in the surface material (A–16). At the place where the samples were taken, the fine particles had no doubt been winnowed from the 7-millimeter thickness of average dune material. In a large dune sampled at Llano Grande, the average top half meter of dune material showed a particle-size peak of 49 percent fine particles. These figures indicate that a high degree of grain sorting is caused by winnowing in the short-lived ripples and dunes but little, if any, within the larger, longer-lived dunes.

On the second of two consecutive days without rainfall during the rainy season, when the surface wind was from the east, the following observations were made at Llano de Huanárucua, where the original aerially deposited ash was 26 centimeters thick: The spacing of small dunes was very irregular, as was their length, but their width (5 to

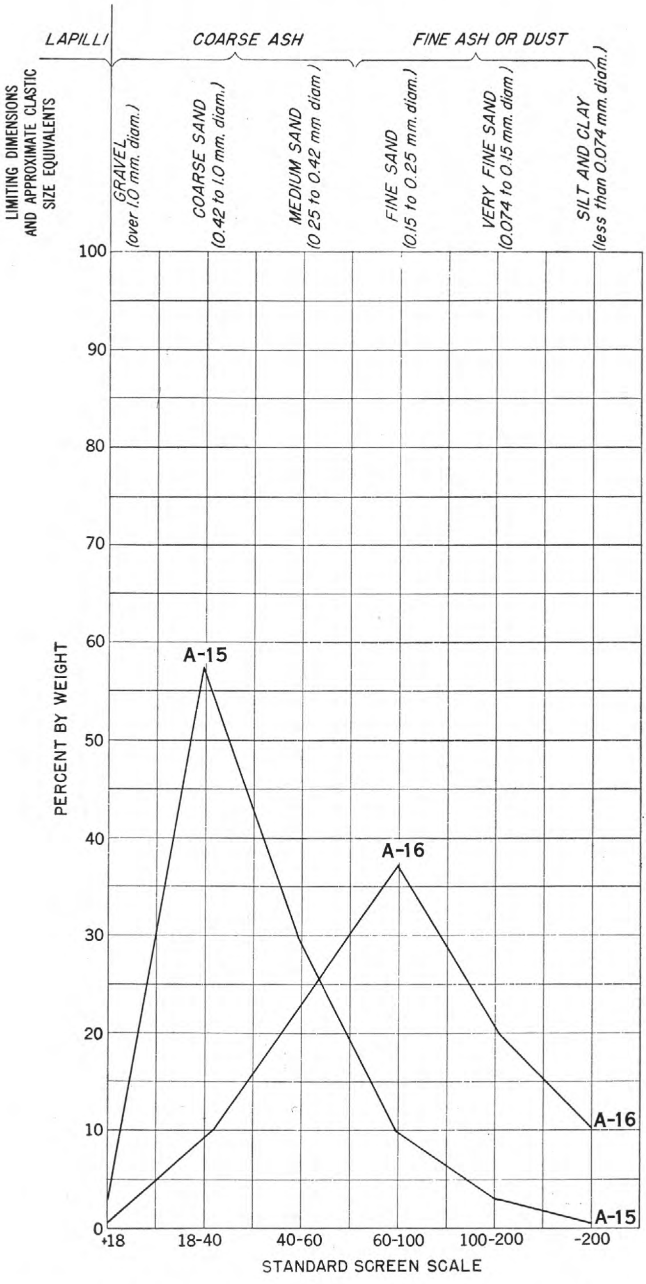


FIGURE 63.—Graph showing size distribution of particles in samples of wind ripples near Parícutin and of the surface between them.

10 centimeters) and their height (5 to 10 millimeters) did not vary widely. The crescentic shape was predominant, but the degree of curvature was less for the longer than for the shorter dunelets. Although the dunes themselves were dry, the flat places between them were damp. The smallest recognizable dune was 4 centimeters long and the largest simple dune 50 centimeters long, but the longest of all were the complex dunes that seemed to be composed of a number of barchans joined at the horns. One of them was 140 centimeters long and 10 centimeters wide, with the most prominent horns at either end. Some complex dunes had branches, and sections of such dunes were almost straight for as much as half a meter. One dune only 7 centimeters long had no neighbors for at least 2 meters in any direction. There was little symmetry in the pattern of dune clusters; sometimes convex places were opposite concave places on the adjacent dune and at other times not. The spacing within clusters was a little more uniform than the shape; there was an average of about eight dunes per meter. The long dunes were about as wide as the short ones (excluding ripples or dunelets less than 8 centimeters long).

On a later visit to Huanárucua an over-all parallel-ripple pattern, rather than irregularly spaced and sized colonies of small dunes, was seen. Locally a southeast wind had cross-rippled the marks made by an east wind, and at places islands of single-direction ripples were surrounded by two-direction marks. Over most of the area the ripples were so close together (11 to the meter) that the spaces between them were covered with loose ash grains that had apparently rolled off the ripples.

The ripples that are arranged in a parallel-line pattern are ordinarily only about 5 centimeters apart from crest to crest and apparently are formed only when the wind blows from one direction. The network pattern of ripples is formed when the wind is variable in direction, which is especially common in the vicinity of large dunes and other obstructions (fig. 64).

During the rainy season, when the ash mantle is wet but dry new ash is deposited directly from an eruption, wind-drifted accumulations of the dry material controlled by the microtopography of the damp surface are sometimes seen (fig. 65). Where the surface is smooth, elongate dunes of dry ash thin down to single grains at the fairly straight but ragged-appearing windward edge. The leeward edge is characterized by highly irregular lobes that extend outward for much greater distances than the average dune width. Minute ridges a few millimeters high appear at many of the leeward edges, with two or three others parallel to them but progressively lower toward the windward edge. The elongate dunelets are as much as 50 meters long,

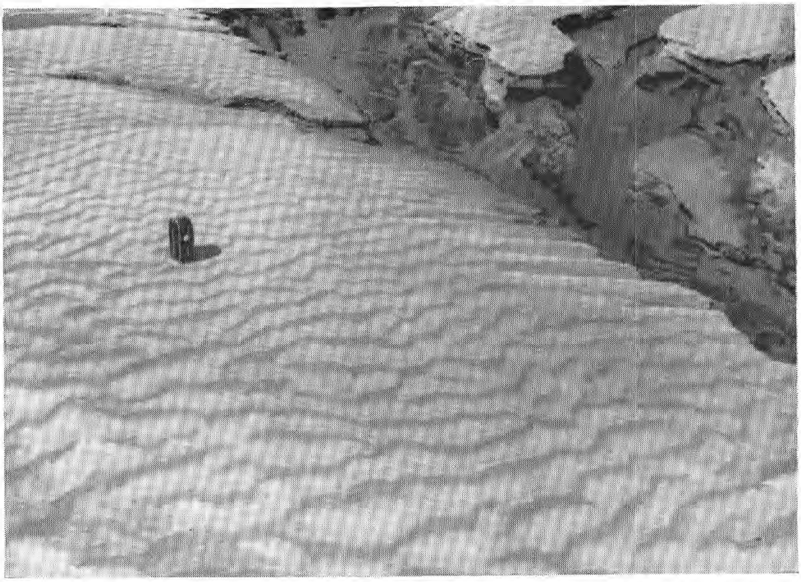


FIGURE 64.—Ripples formed on an arroyo bank in the Parícutin area by winds from different directions.

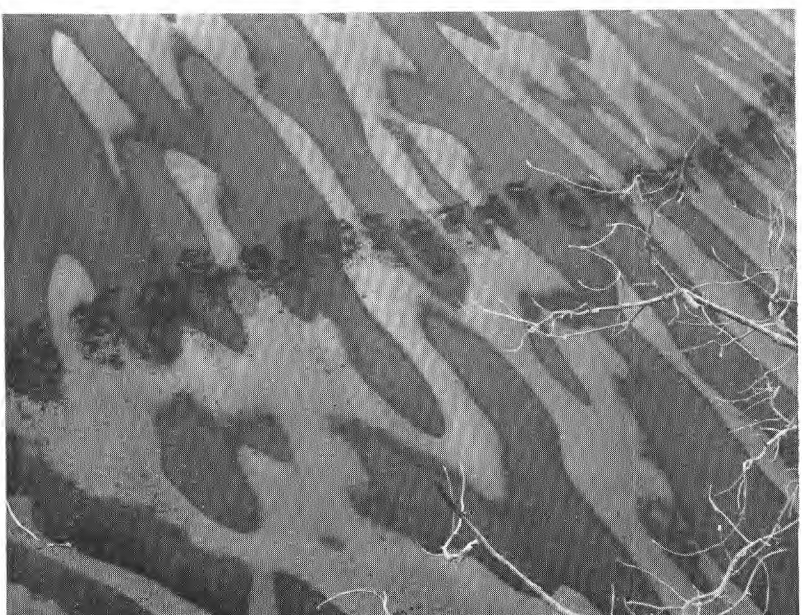


FIGURE 65.—Accumulations of dry ash from a new Parícutin eruption on an uneven surface of damp ash.

with widths varying from a few centimeters between lobes to a meter at the broad-based, narrow-tipped lobes.

Many of the largest dunes in the ash are formed as a result of, or are modified by, obstructions that cause a reduction in wind velocity and a change in its direction. Stone fences oriented across the path of the east and west winds in wide expanses of open country like that at Llano Grande are nearly buried by wind-deposited ash (fig. 66).

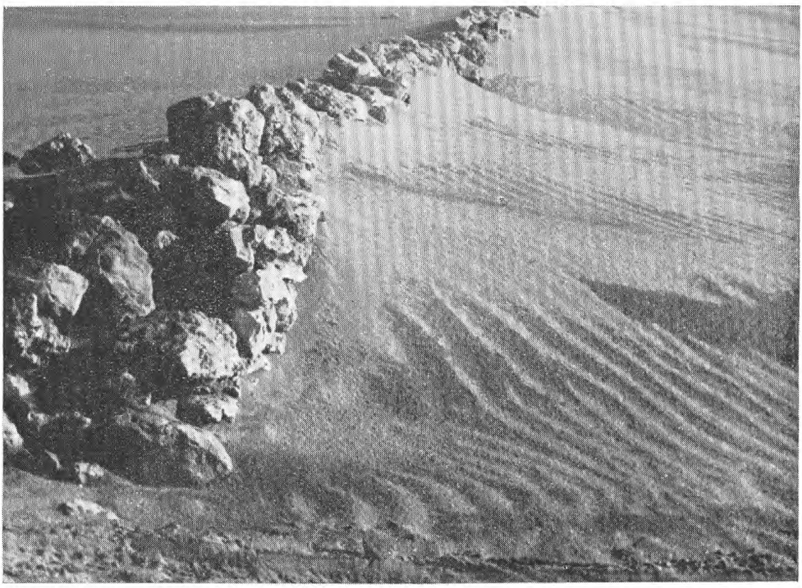


FIGURE 66.—Stone fence on Llano Grande nearly buried by wind-drifted ash from Parícutin.

Little, if any, asymmetry is visible in these deposits, as they are formed by winds from both directions. Hollows form around the bases of wide-spreading trees and maguey plants where the ground is shielded from deposition by branches and foliage, or only on the leeward side, where cross-wind eddies do some scouring.

Arroyos on Llano Grande that have lost their vitality through stream capture are being obliterated by drifting ash. A northward-trending swale that follows the crest of a broad ridge south of Zirosto is intensely channeled by rills on its eastern side, but on its western side wind deposition not only obliterates any channels that might form but provides a more permeable surface that inhibits rill forming.

Although wind direction and intensity are of great importance in initially distributing the ash erupted from the volcano, wind erosion and redeposition occur on a minor scale as compared with water erosion and redeposition. In the mountainous terrain surrounding the volcano there are no large expanses of open country where wind action is unobstructed, although the dust storms of the dry season are impressive enough to give a false impression of the extent of wind sedimentation. R. R. Shrock, who visited the area on May 12, 1944, has written: "It is suggested that wind action, like that which may be observed today in the vicinity of El Parícutin and farther away, may well have played an important role in forming the extensive ash plains of the central plateau of Mexico." [53] As a matter of fact, these Mexican ash plains are characteristically alluvial.

STRIPPING OF ASH MANTLE

The removal of new ash from the area around the volcano is taking place in four ways: (1) by landslides, (2) by the combined effects of raindrop splash and sheet erosion, (3) by channel erosion, and (4) by deflation.

The greatest volume of material removed at any one place up to 1946 was from some of the slopes at Cocjarao, just south of the cone, where on 70- to 100-percent slopes the entire 6-meter thickness of ash has descended in landslides to the border of the Parícutin lava field. Here a maximum thickness of 40 meters, including some interbedded lava, accumulated from 1944 to 1946. At the head walls of old barrancas on the maturely dissected cones of Corucjuata and Cuaxándaran, west of Parícutin, where 3 meters and 1.6 meters, respectively, of ash from Parícutin were originally deposited, slopes with gradients of 100 percent have been completely stripped. The steep sides of the deep gorges south and southeast of Zirosto, where slope gradients of 100 percent are not uncommon, have been completely stripped by landslides of an ash mantle averaging about 1 meter in thickness.

The percentage of the ash mantle removed by raindrop splash and sheet erosion from various slopes to September 1946 is shown in table 10. Where the ash mantle was originally deposited to a depth of 25 centimeters or less on old cones in the vicinity, it has been completely stripped; where the mantle was thicker, the stripping by sheet erosion varied from 70 percent for an original thickness of 33 centimeters to 33 percent for an original thickness of 165 centimeters. On these cones all the ash had been stripped off in stream channels where the ash thickness was less than 165 centimeters; where the mantle was thicker, the channels were as much as 2 meters deep. Channels on the angle-of-repose slopes of the old cones ranged in width from 0.5 meter to 1.5 meters, and the interfluves between them from 1 meter to 4 meters. Assuming a mean channel width of 0.75 meter and a mean interfluve width of 2.5 meters, 100-percent stripping

[53] Shrock, R. R., Sedimentation and wind action around Volcán Parícutin, Mexico: Indiana Acad. Sci. Proc., vol. 55, p. 120, 1945.

in the channels alone accounted for about a 30-percent removal of the entire slope mantle. If the material removed from the interfluves by sheet erosion is added to that removed in the channels, the total proportion removed from areas where the original mantle was 33 centimeters thick amounted to 88 percent and, where it was 165 centimeters thick, about 57 percent.

On slopes of lower gradient and shorter length, the rate of removal is much slower. Some slopes with a gradient of 15 percent were nearly free from channels in 1946, although sheet erosion had removed large volumes of ash (table 10). A slope that has been stripped for most of its length may still have fingerlike remnants of ash mantle extending from the crest, and redeposited ash at the bottom may extend in fingers part way up the stripped slope (fig. 56). On 3- to 6-percent slopes up to 2 kilometers long, erosion and deposition seem to be in balance, and the 1946 mantle was about equal in thickness to the entire original mantle.

The stripping caused by deflation on the rolling plains west of Angahuan has been of some economic importance. The old soil surface exposed on the windward sides of the hills and ridges in that area was being cultivated, but the leeward slopes were still barren in 1946 because they were covered by about 25 centimeters of ash from Parícutin.

Since some areas were completely stripped of their ash mantle, others were not at all affected, and in still others the thickness was increased as a result of deposition, calculations of the average rate of stripping for the whole ash cover and estimates of the time required for complete removal of the ash from the region (5 years from 1945, according to Arias Portillo [54]) are without meaning.

ACCELERATION OF EROSION ON PREEXISTING LAND FORMS

The following factors account for drainage changes and acceleration of erosion on land forms existing before the eruption: (1) Heavier loads of sediment and larger grains have correspondingly greater cutting power in old channels. (2) Killing of the vegetation destroys the protective cover. (3) Some of the rill channels easily formed in ash from Parícutin may continue to erode the old surface after the ash is stripped away. (4) A sudden release of flood waters impounded by lava from Parícutin, by alluvial fans, or in old craters can remove in a few minutes all the ash and a quantity of underlying soil that would ordinarily require many years for its removal.

On the west face of Cerro de Curupichu is a steep-walled amphi-

[54] Arias Portillo, Pedro, La región devastada por el volcán de Parícutin: mimeographed thesis, Escuela Nacional de Agricultura, pp. 46-46, Chapingo, Mexico, 1945.

theater that has been largely stripped of ash from Parícutin. There two small pre-1943 gullies appear to have been deepened by recent pot-hole formation. Sharp-edged, unweathered ash particles and lapilli that are still being brought down these gullies scour out a series of pot holes in the weathered material, as the coarse ash grains left in them show. These pot holes are eroded to a depth of 20 to 30 centimeters below the level of the step on which they occur, or 60 centimeters to 1 meter below the level of the next higher step.

Measurements were made of 10 consecutive barrancas at points about 50 meters up the west side of Cerro de Cutzato, the largest of the old cinder cones in the vicinity of the present volcano, where about 45 centimeters of ash from Parícutin was originally deposited. The barrancas were typically V-shaped, the living vegetation on their sides had been partly thinned out by recent landslides, and their bottoms contained bare, box-shaped inner channels that had probably been eroded since the beginning of the Parícutin eruption. By measuring the depth and width of these barrancas, the width of the interfluves, and the dimensions of the inner channels, it was calculated that about 30 percent of the top 7 meters of Cutzato's surface had been removed by means of barrancas (ignoring sheet erosion) before the Parícutin eruption and about 0.8 percent more since then. If 0.8 percent represents the proportion removed during three rainy seasons, then 30 percent at the same erosion rate would represent a lapse of 112 years since this cone was formed, which is obviously an impossibly small figure but nonetheless of some significance in indicating the acceleration of erosion on Cutzato due to ash from Parícutin.

The dissection of local land forms that took place before the eruption of Parícutin must have been similarly accelerated during brief periods following each eruption of an earlier volcano.

In the channel of the Rio de Itzícuaro at Zirosto, only about half a meter of deepening appears to have taken place since the eruption of Parícutin. From there on downstream, the base level of the river is so controlled by successive lava crossings that most of the recent cutting appears to have been lateral rather than vertical. This is true of most of the barrancas tributary to this river. As a result, many of the gorges that were formerly V-shaped have had their floors widened without a corresponding widening of the distance from rim to rim and are now steeper-sided than before. The greater steepness of the sides brings about an unstable equilibrium, which thus far has not produced much landsliding but will from time to time cause slides and a widening of the distance from rim to rim of all the principal barrancas in the area around Zirosto.

Far downstream, dumping of the sediment load has temporarily blocked old channels of the Rio de Itzícuaro and caused the cutting of others. Just south of the sugar factory at San Sebastián, for example, an arched masonry bridge has been left standing at one side of the river, which cut a new box-shaped channel 2 meters deep across the northern approach to the bridge.

Areas south and west of Parícutin that have been denuded of vegetation and lie in the path of floods that descend from Cerros de Tancítaro show greater acceleration of erosion since 1943 than the wooded slopes of Cutzato and those along the Río de Itzícuaro. A comparison of aerial photographs taken before and after the eruption reveals that several large barrancas now exist where there were none before. The largest of these is west of the Cocjarao triangulation station. It was about 10 meters deep in 1946, and the bottom 3.5 meters was eroded in soil and rubbly lava that existed before the eruption. At the south base of Cerro de San Pedro, a drain that was only a shallow swale before 1943 was 5 meters deep and 2 meters wide where it was eroded down into preexisting soil and tuffs. Where it passes over an old lava flow, it was 2 meters deep and 5 meters wide.

According to Celedonio Gutiérrez, the approach to Cerros de Tancítaro from the north was formerly without obstacles. At present, however, the way is made difficult not only by several new arroyos but also by the posteruption cutting of box-shaped inner channels in the old V-shaped barrancas. Such obstacles can be crossed only by following the channel to a lava crossing, which is always a place of widening and decreased depth. The steepness of the slopes and the enormous volume of ash being stripped from them have combined to give great force to the floods that rush down the old barrancas of Tancítaro and cause much landsliding of rubbly lava, which is deposited as boulders on fans hundreds of meters beyond the base of the mountain. South of the summit of Cerros de Tancítaro, the thickness of aerially deposited ash from Parícutin is not great enough to accelerate erosion to any appreciable extent.

Before 1943, the youthful cone of Loma Larga was undissected except at the breached west side. Since the eruption, 5 meters of ash has been deposited over Loma Larga, and by 1946 this mantle was deeply dissected, although not yet to the underlying soil. The concentration of runoff in ash barrancas for some length of time will eventually cause deepening to the old surface and dissection of the preexisting soil on the sides of this cone, and these scars will remain after the Parícutin mantle has been completely stripped away.

The release of floodwaters impounded by lava from Parícutin has produced large-scale channel cutting into the underlying soil, tuffs, and agglomerate at the east edge of the new lava field. The process of integration of several isolated basins near the Curínguaro triangulation station by overflow from one small basin to the next was accompanied by the cutting of barrancas to a depth of 5 or 6 meters into the old soil on the bases of hills where there were no channels before 1943. Another example of this process is the carving out of the Casita Canicjuata barranca (see p. 37). A great rush of floodwaters down Arroyo de Corucjuata in 1944 formed a boulder-strewn alluvial fan as much as 6 meters thick, completely blocking the course formerly followed by this stream. A new channel from 9 to 12 meters deep, half of which was eroded in preexisting material, was carved for a distance of about a kilometer before the stream finally returned to its old course.

An unbreached crater of the Curitzerán cinder cones lacked in 1946 only 1.5 meters of further ash redeposition on its floor for runoff to flow over the lowest part of the rim. This will probably be accomplished by a continued stripping of the ash from the inner walls of the crater. The result will be the breaching of one side, an obvious acceleration of erosion.

APPENDIX

NOTES ON EROSION AT JORULLO

By Kenneth Segerstrom

On September 29, 1759, at about 3 a. m., Jorullo volcano began an eruptive activity that continued for 15 years. Like Parícutin it emerged from new ground, although in a region of young basaltic cones. Jorullo is in the State of Michoacán about 72 kilometers by air line southeast of Parícutin, near the south edge of the same area of recent volcanism. The immediate setting was so fertile before the eruption that the area was known as Paradise, or El Jorullo in the language of the Tarascan Indians. The old hacienda of San Pedro de Jorullo was near Cerro Partido, now called Cuchilla Atrozada, a doleritic ridge [55] that rises just northwest of the present cone.

An eyewitness named Sáyago kept a diary of the events of September–November 1759.[56] The eruption was preceded by earthquakes and subterranean reports near the end of June 1759, and the first damage to the hacienda was caused by a mudfall composed of a mixture of condensed vapors and ash that covered the land during the last 2 days in September. Ash driven by the prevailing east wind of the rainy season covered La Huacana, a town about 12 kilometers to the southwest. This ash caved in the roofs of houses, and the town had to be abandoned by October 6. Streams heavily laden with ash sediment flooded much of the broad valley from La Playa to La Huacana. Continued heavy emission of pyroclastics had by November 13, when Sáyago's diary ends, built a circular crater about 250 meters high. Ash falls destroyed the pastures at Oropeo, 20 kilometers south-southwest of the volcano, and were recorded as far away as Querétaro, about 235 kilometers to the northeast. The lava flows may not have appeared until as late as 1764, which has been considered the year of greatest eruptive activity. An area of 9 square kilometers was covered by new lava, the last flow of which covered the north side of the cone itself. Three satellite cones, with the main cone, form a line trending approximately northeast (pl 7)—the same direction, incidentally, as the line joining Sapichu with Parícutin and Mesa de Los Hornitos.

Gadow [57] concludes that the main features of Jorullo had reached their present size by 1766, although some eruptive activity was

[55] Ordóñez, E., Le Jorullo: 10e Cong. géol. internat., Mexico, Guide Exc., no. 11, 1906.

[56] Orozco y Berra, M., Jorullo (Volcán de): Diccionario de historia y geografía, vol. 4, p. 453, 1854.

[57] Gadow, H., Jorullo, p. 6, London, 1930.

reported as late as 1774 and fumarolic activity still continued in 1946. After the last lava flow there was no appreciable emission of pyroclastic material, for this flow is bare. The rest of the lava field is thickly mantled by ash, the surface of which to the west of the volcano is dotted with little mounds, many of which probably cover the "hornitos" described by Baron von Humboldt. These are apparently the sites of fumaroles rather than spatter cones, as Humboldt states. Gadow describes the occurrence on the lava field of hummocks "a few feet high, sometimes not larger than a cartload of sand dumped down and then smoothed over." [58] The mounds are capped by indurated layers of ash "having from the thickness of a book cover to a half inch or more." [59] Other hummocks are composed of lava not capped by ash.

Plant life was completely destroyed by the ash from Jorullo in an area that bears a remarkably close resemblance in size and shape to that enclosed by the 1-meter isopach at Parícutin, which may be considered the approximate limit of total devastation at the newer cone. The vegetation that has reclaimed the area around Jorullo is largely tropical, whereas that reclaiming the ash at Parícutin is of the Temperate Zone; yet the nature of the recovery at the older cone indicates what may happen at the new one. By 1803, according to Humboldt, La Playa (5 kilometers west-northwest of Jorullo) had much vegetation,[60] although the original ash deposits there must have been at least 1.5 meters thick, judging from the Parícutin isopachs. However, admixtures of redeposited soil—for this was an area of flooding—must have hastened reclamation at La Playa. By 1827, vegetation had already reclaimed part of the ash-covered lava area, according to Burkart,[61] and 20 years later trees were growing on the sides of the cone. "Practically, the flora had reclaimed the lost ground by the middle of last century, say within 90 years of the catastrophe." [62]

The writer visited Jorullo on two occasions: in February 1946, for an ascent of the volcano, and in December 1946, accompanied by R. E. Wilcox and Ariel Hernández Velasco, for a plane-table survey of the cone and its satellites (pl. 7). The following observations were made:

Just before reaching Vallecitos, about 8 kilometers west of the volcano on the road from Ario de Rosales, the gray volcanic ash first appears plainly on the road and in the creek beds. The nearby young

---

[58] Gadow, op. cit., p. 18.

[59] Idem.

[60] Humboldt, A. von, Kosmos, vol. 4, p. 562, Stuttgart, 1858.

[61] Burkart, H. J., Aufenthalt und Reisen in Mexiko in den Jahren 1825 bis 1834, vol. 1, p. 227, Stuttgart, 1836.

[62] Gadow, op. cit., p. 27.

cone of Cerro Pelón is practically ungullied, although it must be much older than Jorullo.

The west slope of La Playa valley is covered with royal palm, strangler fig, and fields of corn and squash; the east slope with grass, sparse brush, and scattered trees. The east side of the valley is mantled by lava from Jorullo, which is covered by gray ash except for the bare mass of lava on the north side of the cone. The round cones of Jorullo, Volcancito del Norte, Volcancito del Sur, Cerro del Veladero and Cerro Pelón are in striking contrast to the maturely dissected intrusive-rock mountains just south of Cerro Pelón and Jorullo and to the equally dissected escarpment of massive flows and tuffs that forms the Mesa Central to the north and east.

On the lava field west of the cone, the gray ash is so loose when dry that walking is difficult in the cowpaths and stream beds, and it is easier to walk over the thin grass on either side of the traveled routes. Many of the numerous mounds that dot the lava plain are very small elongated ridges covered with indurated ash. The crests of some of these minor elevations are broken by fissures ranging in width from several millimeters to several centimeters. The fissured ridges are as much as 30 centimeters but commonly about 20 centimeters wide and continue, with some branching, for distances of a few meters to 20 or 30 meters. No hot air issues from the cracks, and long-stemmed grass grows in them. The fumarolic gases that formerly issued from these fractures probably indurated the narrow zones of cemented ash on either side. Erosion has removed enough loose ash from either side to cause the indurated zones to stand about 30 centimeters above the surrounding ground. Other mounds, subcircular in shape, have no fissures visible at the surface. They are apparently the hummocks aptly described by Gadow (p. 136), but they perhaps do not overlie extinct fumaroles. Mounds similar in shape and setting, ranging from 15 to 25 feet in diameter and 1 foot to 6 feet in height, have been described from the Columbia River Plateau. According to A. C. Waters and C. W. Flagler, the mounds of this plateau are erosion remnants of a volcanic ash mantle deposited on a relatively smooth lava surface. Their development is attributed to subaerial water erosion.[63]

At the west and southwest bases of the main cone, a few very recent mudflows formed of coarse particles were seen. One of these, about 1 meter wide and 10 centimeters thick, was dissected down the middle by a channel 20 centimeters deep; another, 2 meters wide and 35 centimeters thick, with several distributaries, was dissected in the middle to a depth of 65 centimeters. The slope gradient in the area

[63] Waters, A. C., and Flagler, C. W., Origin of the small mounds on the Columbia River Plateau: Am Jour. Sci., 5th ser., vol. 18, p. 209-224, 1929.

of the distributaries of the larger mudflow was 24.5 percent. Seven other mudflows observed ranged in width from 0.5 meter to 2 meters, and the slope gradient of the last 4 or 5 meters of their courses averaged 16 percent. The particle size of the material in these flows ranged from coarse ash to lapilli and scoria as much as 10 centimeters in diameter.

The south slope of Jorullo is fluted with gullies, the interfluve spaces forming about one-third of the area and the gullies two-thirds. The surface ash has become indurated on the interfluves and down the barranca sides for distances ranging from 10 centimeters to 1 meter, below the interfluves, but the barranca floors are of loose material. The gullies on the south side of the cone range from 2 to 7 meters in width and from 0.5 meter to 3 meters in depth. Eastward from this side the barrancas are spaced farther and farther apart until the interfluves are about three times as wide as the gullies. On the east side the zone of gullies ends abruptly (fig. 67), leaving only

FIGURE 67.—East side of Jorullo's main cone, showing both intense gullying (left) and no gullying (right).

a few shallow, ill-defined swales and one short barranca that descends from a saddle in the rim. Most of the north side is formed of the rugged surface of the final Jorullo lava flow and has no ash cover. On either edge of the lava, barrancas have formed at the reentrant between the lava and the ash slope; the only other ash gully on the north side appears to have been formed in the reentrant between the ridge of Cuchilla Atrozada and the cone, from which it has extended itself by headward retreat toward the rim of the crater. The west side also is gullied, although not so intensively as the south side. About half the circumference of Jorullo, therefore, shows channel erosion, whereas the rest does not (pl. 7).

Three explanations of the unequal dissection on different sides of Jorullo may be advanced: (1) Most of the surface material on the east side of the cone is noticeably coarser than most of that on the south and west sides, resulting in a surface of unequal permeability over the cone. Inclined explosive vents may have ejected coarser material to one side than to the others. (2) The prevailing west wind during the dry season (when the surface is most easily removed) has swept away the loose material from the more exposed west and south slopes down to the first compact (generally fine-grained) bed, thus decreasing the surface permeability. This explanation would apply also to Volcancito del Norte and Volcancito del Sur, where the unequal dissection on different sides corresponds to that on the main cone. (3) The west and south sides of the cone are those of greatest slope length, an important factor in channel erosion.

The largest gullies formed in ash from Jorullo are those south of the base of the main cone, where great thicknesses of beds are exposed (fig. 68). The ash is indurated to a depth of about 5 centimeters on narrow, convex interfluves. This induration seems to have occurred after initial dissection of the ash, because the convexity of the indurated beds is that of an eroded surface rather than a smooth constructional surface. Everywhere the ash is gray, indicating that weathering has not been sufficient to alter the color.

The drainage trapped by the Jorullo lava field at La Alberca is that from the long escarpment of the Mesa Central to the east of the main cone. The preeruption slope gradient of the volcano site may have been about 5 percent, judging from the gradient of the lava field to the west of the cone, which indicates that the surface of the present sink at La Alberca was about 60 meters lower than it is now. If this basin were filled with 20 meters more of sediment, it would overflow between the main cone and Volcancito del Norte. Two very small sinks are at the north edge of the lava field. The spring at Rancho de La Escondida, near the west base of Volcancito del Sur, and the seeps at the sides of Barranca Puerca may represent the emergence of part of the trapped-drainage flow after it passes through the lava field, a phenomenon like that of the sudden flow increase at Sipicha, near Parícutin, a year after the San Juan lava flow blocked many square kilometers of drainage basin.

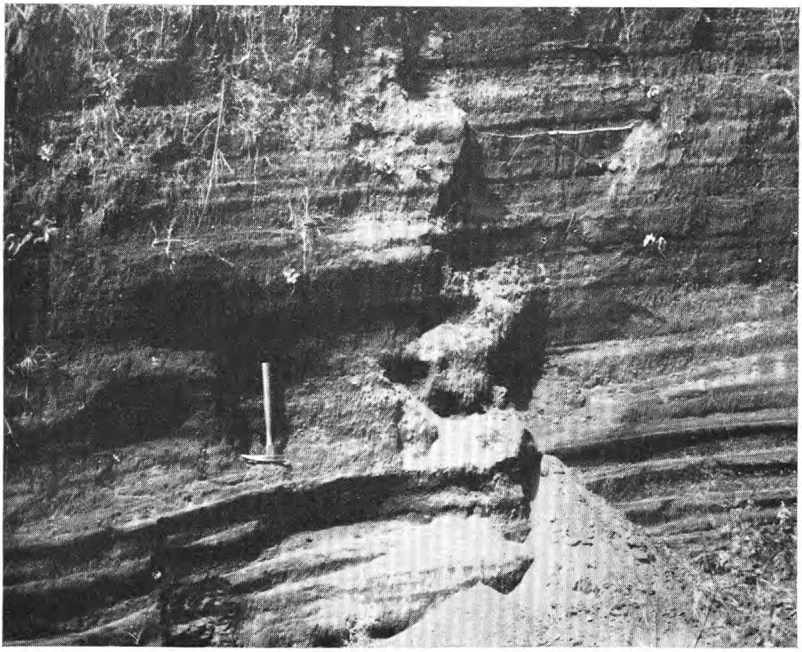


FIGURE 68.—Bedding in ash from Jorullo exposed in Barranca Puerca, south of the cone.

There is no evidence of water erosion within the crater. Open concentric fissures on top of the rim, as much as 2 meters wide, indicate the nature of the slumping inside the crater, which has a stepped-down character. Some of the steps are covered with wedges of talus from above, but of material too permeable for rills to form. Scattered oaks, about half a dozen pines, and several other varieties of trees and bushes find lodging, however, in the coarse material lying on lava ledges within the crater. One pine about 30 centimeters in diameter is growing near the bottom, and three oaks each about 20 centimeters in diameter appear still farther down. Only near the rim and at the north end of the bottom trough is grass growing within the crater.

COMPARISON OF PARICUTIN AND JORULLO

PARICUTIN	JORULLO
Place of birth	
A small, nearly level, sometimes cultivated clearing among forested hills.	A fertile amphitheater floor.
General setting	
Well inside a large area in the State of Michoacán covered with recent volcanic material, mostly basaltic.	Near the south edge of the same area of recent volcanics.

Accessibility

Five kilometers south of a main valley (San Juan), accessible by automobile.	Five kilometers east of a main valley (La Playa), accessible by automobile.

Elevation of summit above sea level

2,760 meters.	1,330 meters.

Apparent height above lava field

About 260 meters above north base and 150 meters above south base in 1946–47.	About 380 meters above west base and 230 meters above east base.

Average thickness of lava around base of cone

About 100 meters.	About 100 meters.

Maximum diameter of apparent base of cone

1,100 meters in 1946–47.	1,300 meters.

Maximum diameter of top of crater

360 meters in 1946–47.	550 meters.

Satellite cinder cones

One.	Three.

Area covered by lava flows

About 22 square kilometers in 1946-47.	About 9 square kilometers.

Shape and size of zone enclosed by 1-meter isopach

Egg-shaped, about 61 square kilometers in area, extending much farther west of cone than east. Distances, in kilometers, outward from cone to edge of zone: West ---- 6. 8 East ---- 3. 8 Northwest ---- 6 North ---- 4 South ---- 2. 8	According to Gadow,[1] about 68 square kilometers in area, extending much farther west of cone than east. Distances, in kilometers, outward from cone to edge of zone: West ---- 8 East ---- 3. 2 Northwest ---- 6. 4 North ---- 3. 2 to 4. 8 South ---- 3. 2 to 4. 8

Orientation of vents

Approximately S. 45° W. from center of crater to center of Hornitos area; approximately N. 45° E. to Sapichu; approximately S. 30° to Ahuán area.	S. 42° W. from deepest part of main crater to tops of Volcancito de Enmedio and Volcancito del Sur; N. 30° E. from deepest part of main crater through top of Volcancito del Norte.

Rate of vertical growth of cone

140 meters in first 35 days; 198 meters in first 106 days.[2]	250 meters in first 45 days.[3]

---

[1] Gadow, H., Jorullo, p. 23, London, 1930.

[2] Flores, Teodoro, and others, El Parícutin, Estado de Michoacán, plate, p. 152, México, D. F., Instituto de Geología, 1945.

[3] Gadow, H., op. cit., p. 6.

NOTES ON EROSION AT CEBORUCO

By Kenneth Segerstrom

On February 23, 1870, at 3:00 p. m., the large composite cone of Ceboruco began its first activity in historic times, although there is evidence in the lava flows and ash slopes of at least four distinct earlier periods of eruption. This latest emission of pyroclastics lasted until 1872; Miguel Iglesias reports that some lava still continued to flow during that year.[64]

Ceboruco is located in the State of Nayarit, 300 kilometers northwest of Parícutin or about 135 kilometers by air line west-northwest of Guadalajara. From the town of Xala, about 5 kilometers northeast of the base, the ascent via Coapan to the northeast rim of the crater may be made on foot up a long ash slope in about 4 hours without crossing any lava flows. The ascent of the mountain is very difficult from other sides because of the presence of much rough ceborucal, the local name for lava.

The diameter of the volcano is about 9 kilometers at the base and about 3 kilometers at the top. The highest part of the summit is 2,164 meters above sea level, while the altitudes of points near the base vary from 1,269 meters at Coapan on the east side to 770 meters in the main arroyo just west of the volcano. Parts of three concentric cinder-cone rims rise from the broad summit. The latest eruption emitted basaltic material, but the products of earlier eruptions were andesitic.

Before the eruption of 1870–72, a thick growth of oaks and pines covered the mountain except for the lava flows not mantled by ash. The barren appearance of some of the lava before 1870 indicates that a previous eruption had probably occurred not long before, although there is no record of one. It is reported that during the early stages of the strong 1870–72 eruption the sun was obscured and the leaves of plants were buried. All the vegetation on the mountain was killed, and by 1875 many of the dead trees had blown down. None of the trees on the surrounding mountains were killed by the eruption, but this is not strange when the great size of the volcano and the long distance to which the ash would have had to be carried are considered; the area of about 75 square kilometers covered by Ceboruco is greater than the zones of complete devastation at Parícutin and Jorullo.

[64] Iglesias, Miguel, El Ceboruco: Informe y colección de artículos relativos a los fenómenos geológicos verificados en el presente año y en épocas anteriores, vol. 1., pp. 93–127; vol. 2, pp. 321–342, Guadalajara, 1875.

By 1926, when Tomás Barrera visited the mountain, scattered pine trees were growing on the summit of the volcano.[65]

The following observations on erosion at Ceboruco are the result of a visit to the volcano in March 1947 with Celedonio Gutiérrez:

Gray, unweathered ash is much more noticeable on the east and northeast sides of Ceboruco than on the south and southwest, possibly because the period of maximum ash fall during the 1870–72 eruption occurred during the dry season, when the prevailing winds were from the west. The wide plain between Xala and Coapan is covered with loose gray ash, in which chicolote, salvia, and a few other plants have found some lodging for their roots.

The northeast slope of the volcano is planted in corn almost halfway to the summit on the interfluves between large barrancas and even on the steep sides of some of the barrancas. Desmontes—clearings made by cutting and burning the brush—are extended farther and farther up the slope each year in preparation for cultivating new corn patches. The upper third of the mountainside is wooded, mostly by oaks but also by scattered pines, madrones, and other trees. The very coarse ash and lapilli mantling this slope form a surface too permeable at present to be eroded by water, and the steep fields have no rill channels except in the cowpaths. The deeply incised V-shaped barrancas on this side of the mountain, however, indicate a high degree of dissection of an old constructional surface, which must have been covered by finer, less permeable ash than that at the present surface.

Between the concentric crater rims on top of the mountain is a series of flat-floored depressions covered with fine-grained loose ash sustaining a sparse growth of grass, lechuguilla, salvia, and an occasional pine. The depressions are separated from each other by small lava flows and by remnants of the rims of the smaller-diameter inner craters. On the sides of these craters well-developed planezes in miniature occur between the numerous channels that striate the slopes (fig. 69). Examination of the planezes reveals that the surface material is composed largely of coarse lapilli and scoria, with moss and other small plants growing in the interstices.

It is probable that during the 1870–72 eruption, or at least during its last phases, finer-grained pyroclastics than those now seen on the slopes of the volcano were ejected and formed a relatively impermeable mantle on the small inner craters. Some of the new gullies, easily formed in the fine ash, continued to deepen after they reached the coarse underlying beds. After the fine ash had been stripped from the interfluves as well, the remaining surface shed little or no water into

[65] Barrera, Tomás, Zonas mineras de los Estados de Jalisco y Nayarit: Inst. geol. México Bol. 51, photograph, p. 42, 1931.

FIGURE 69.—Part of the upper slope of Ceboruco, State of Nayarit, Mexico, showing planezes in miniature.

the gullies; erosion ceased, and moss and grass took root on the dissected uppermost slopes of Ceboruco. The lower slopes, situated farther from the eruptive throats of 1870–72, were not as deeply covered by the fine, new ash. Stripping was so rapid that both gullies and interfluves were gone before the coarse beds underneath were appreciably dissected. Hence, the long outside slopes, although deeply scarred by large old barrancas, do not exhibit the same pattern of new gullies.

The fine material removed from the sides of the inner craters was redeposited in the depressions between the crater walls, whereas that removed from the outer slopes was redeposited in broad areas like the one between Xala and Coapan. Deposits from the craters (sample CE–4) are less fine grained than the ash deposits at the base of the mountain (sample CE–1), as shown graphically in figure 70.

A landslide on the south face of the highest inner crater, known as La Coronilla, has left a nearly vertical scar about 30 meters high in which bedded pyroclastic material is exposed (fig. 71). Another landslide in a gully on the south side has exposed beds with an original dip somewhat greater than the slope surface, indicating that this surface is old enough to have been slightly flattened by water deposition (fig. 72).

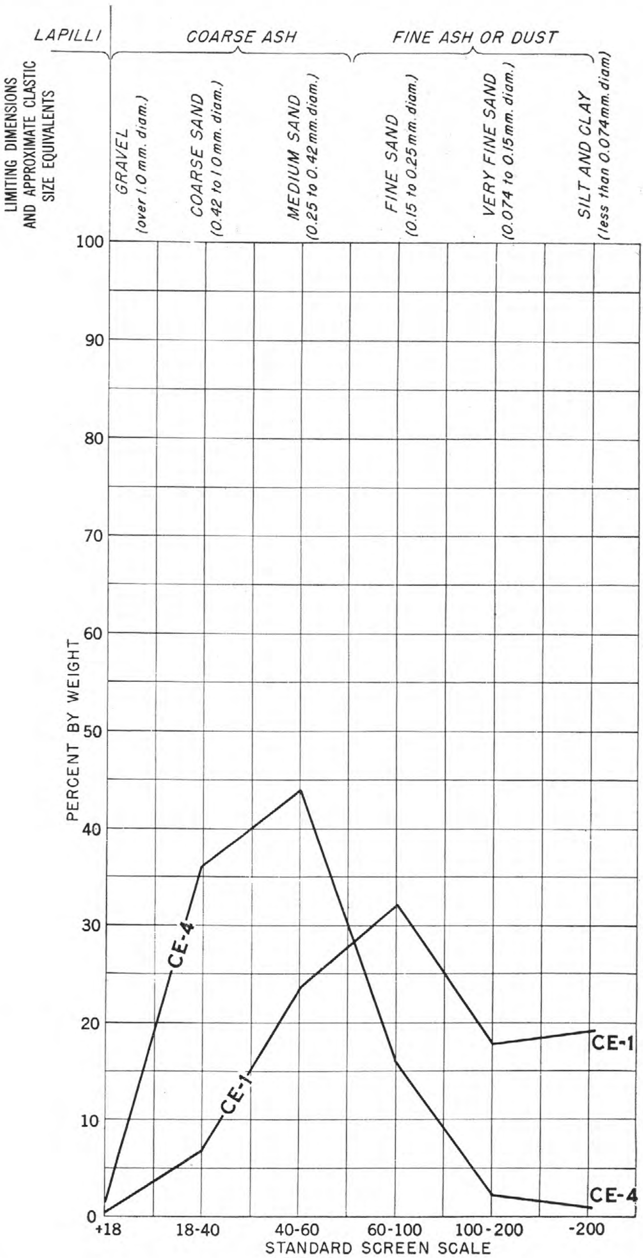


FIGURE 70.—Graph showing size distribution of particles in samples taken from surface at south base of Ceboruco (CE-1) and from surface between inner and outer craters (CE-4).

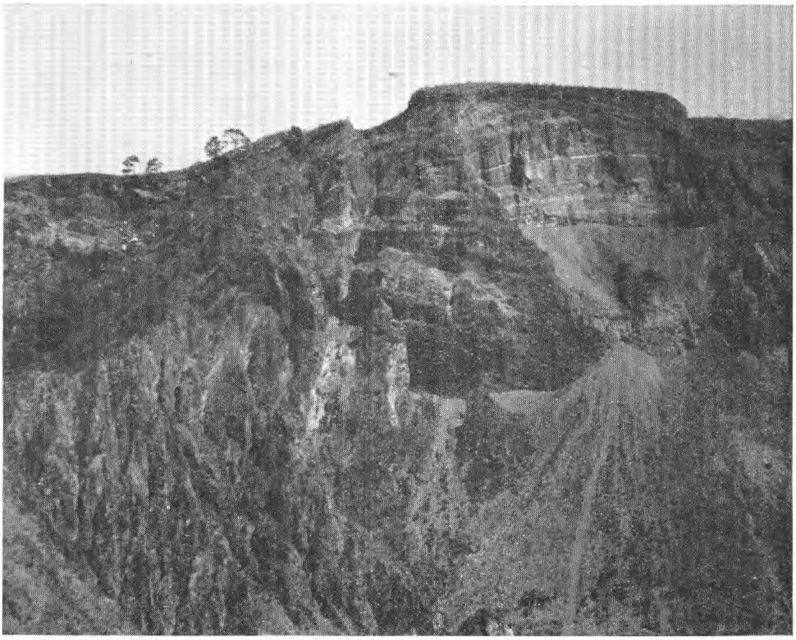


FIGURE 71.—Bedding of ash exposed by a landslide on the west face of La Coronilla, highest inner crater of Ceboruco.

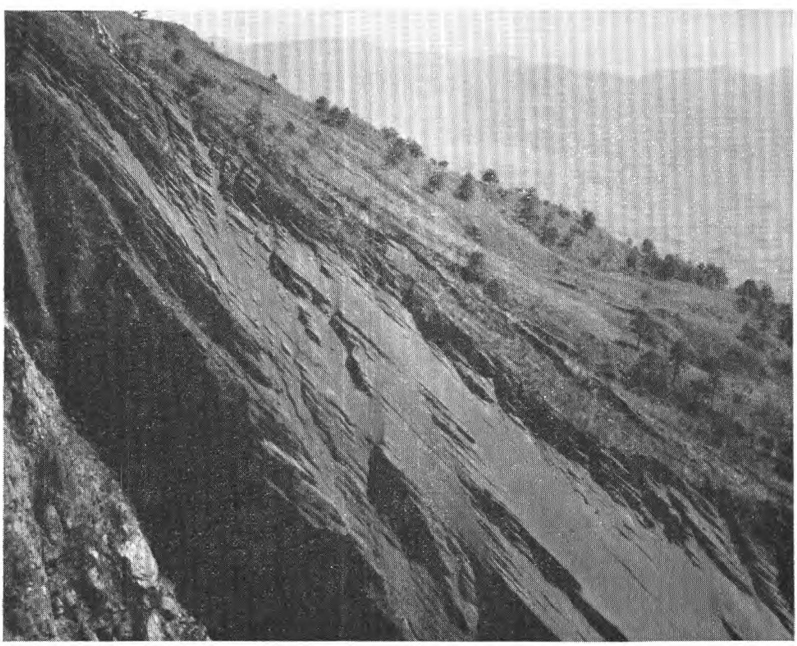


FIGURE 72.—Landslide action at the head of a barranca on the south side of Ceboruco has exposed ash beds showing the original dip.

The south and west sides of the volcano are the scene of many superimposed lava flows buried by different thicknesses of ash. Some of these flows extend far out into the valley of Ahuacatlán, and one has dammed two barrancas that drain a much older ash-mantled flow whose outcrops are rounded by erosion. On the floor of each alluvium-filled basin thus formed, a well-tended cultivated field contrasts with the surrounding untended brush (fig. 73).

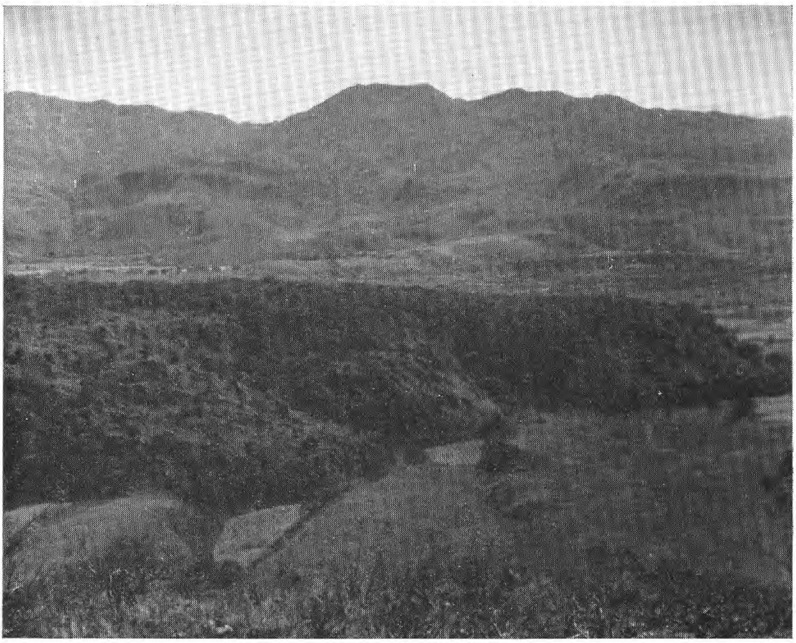


FIGURE 73.—Barrancas dammed by a lava flow from Ceboruco and filled with alluvium have become cultivated fields.

LOCATION AND DESCRIPTION OF ASH SAMPLES TESTED

By Kenneth Segerstrom

A–1. Canicjuata crater; top crust, 3.5 millimeters thick.

A–2. Canicjuata crater; coarse-grained bed, 4 centimeters thick; 1 meter below surface.

A–3. Canicjuata crater; fine-grained brown layer, 10 centimeters thick; 69 centimeters below surface.

A–4. Canicjuata crater; very coarse grained bed, 16 centimeters thick, resting on fine-grained brown layer; 1.19 meters below surface.

A–5. Canicjuata crater; representative of bottom 10 centimeters; 5.6 meters below surface.

A–6. Canicjuata crater; coarse-grained, poorly defined bed; 3.6 meters below surface.

A–7. Canicjuata crater; representative of 10 centimeters at depth of 1.7 meters below surface.

A–8. Mudflow at foot of Las Pirámides (not shown on pl. 1, because later covered with lava); upper end of terminal lobe.

A–9. Mudflow at foot of Las Pirámides; channel fill just above lowest lobe.

A–10. Mudflow at foot of Las Pirámides; side of furrow just above lowest lobe.

A–11. Summit of Cuaxándaran; coarse-grained layer, 1.5 centimeters thick; 30 centimeters below surface.

A–12. Summit of Cuaxándaran; finest-grained layer, 2.5 centimeters thick; 15.5 centimeters below surface.

A–15. Llano de Huanárucua; representative of barchanlike wind ripples.

A–16. Llano de Huanárucua; top layer of ash; not covered by dunes, still damp when dunes (ripples) were dry.

A–17. Jarátiro ridge; fine-grained bed, 23 centimeters thick; 3.89 meters below surface.

A–18. Jarátiro ridge; representative of next 41 centimeters above sample A–17.

A–19. Jarátiro ridge; representative of 38 centimeters of fine-grained ash, but with two thin layers of coarse-grained ash, beginning 133 centimeters above bottom.

A–20. Jarátiro ridge; bed of coarse-grained ash, 11 centimeters thick, beginning 223 centimeters above bottom.

A–21. Jarátiro ridge; representative of 54 centimeters of fine-grained ash on top of sample A–20.

A–22. Jarátiro ridge; very coarse grained bed, 6.5 centimeters thick, beginning 317 centimeters above bottom.

A–23. Jarátiro ridge; coarse-grained bed, 5.5 centimeters thick, beginning 339.5 centimeters above bottom.

A–24. Jarátiro ridge; finest-grained part of top layer of 50 to 60 centimeters of unstratified fine-grained ash.

B–21. Pit at Casita Canicjuata; representative of zone of very fine grained ash extending from 25 to 42 centimeters below surface.

C–1. Fresh ash, 3 millimeters thick, at northwest base of cone, August 28, 1946.
C–2. Very fine grained whitish powder on ash crust near Obispo.
C–3. Fresh ash, 1 millimeter thick, from slope east of Cuaxándaran and north of Cerro del Pueblo Viejo, September 6, 1946.
C–4. Pit on knoll on Llanos de La Caja; average of top 29 centimeters of fine-grained brown ash.
C–5. Pit on knoll on Llanos de La Caja; bed of coarse-grained ash, 1.8 centimeters thick; 54.8 centimeters below surface.
C–6. Pit on knoll on Llanos de La Caja; bed of fine-grained ash, 16 centimeters thick; 162 centimeters below surface.
C–7. Pit on knoll on Llanos de La Caja; bed of coarse-grained ash, 50 centimeters thick; just under sample C–6.
C–8. Pit on ridge of old lava about 2 kilometers south of Llanos de La Caja; top layer, 2 centimeters thick.
C–9. Pit on ridge of old lava about 2 kilometers south of Llanos de La Caja; average of layer of medium coarse grained ash, 26 centimeters thick; 73 centimeters below top.
C–10. Llanos de Bermúdez; fine-grained ash representative of total thickness of 46 centimeters.
C–11. Barranca Seca; fresh ash deposited on top of car in 2 or 3 hours; September 13, 1946.
C–12. Río de Itzícuaro near San Francisco; water-deposited ash from river bank.
CE–1. Surface ash from south base of Ceboruco.
CE–4. Very loose surface ash between inner and outer craters of Ceboruco.
D–1. Fresh ash collected from top of car at Cuezeño, October 11, 1946.
D–2. Fresh ash shaken from leaves of tree at Huirambosta, October 11, 1946.
D–5. Ash fall collected on sheets of paper halfway down west slope of Casita Canicjuata ridge, October 11, 1946.
D–9. Top bed of fine-grained new ash, 1 centimeter thick, on top of lava near Casita Canicjuata, October 11, 1946.
D–12. Fresh ash that fell on new trail just south of Jarátiro during previous 24 hours, October 11, 1946.
D–13. Fresh ash, 4 millimeters thick, scraped from rock at upper rain gage, October 11, 1946.
D–14. Fresh ash scraped off log at Tipacua, October 12, 1946.
D–15. Fresh ash scraped off log at Curínguaro, October 12, 1946.
D–16. Top 8 centimeters of coarse-grained ash on top of lava 110 meters west-northwest of base of cone, October 15, 1946.
D–22. Reddish-tinged surface ash on slope of Canicjuata just above edge of new lava.
D–23. Mud-crack material, 3 centimeters thick, from surface of lava-dammed lake at Chórotiro.
D–24. Coarse-grained material just under sample D–23; not cracked.
E–6. Stream-cut ridge about 3 kilometers northwest of Parícutin; bed of brown soil, 13 centimeters thick, between 23 and 24 meters below preexisting surface.
E–14. Stream-cut ridge about 3 kilometers northwest of Parícutin; bed of dark reddish-brown soil, 15 centimeters thick, about 9 meters below preexisting surface.
E–27. Stream-cut ridge about 3 kilometers northwest of Parícutin; ocher-colored weathered material immediately under preexisting ground surface.
J–1. Representative of material in infiltration tubes at Jarátiro; ash from Parícutin.

M–1. Representative of material in infiltration tubes at Cocjarao; ash from Parícutin.

M–3. Representative of material in infiltration tubes at Llano Grande; ash from Parícutin.

M–5. Representative of material in infiltration tubes at Cuezeño; ash from Parícutin.

M–7. Representative of material in infiltration tubes at Cuezeño; soil beneath volcanic deposits.

W–1. Flood sample taken at Llano Grande; 11.3 percent solids by volume.

W–4. Storm flow in small stream running through ash from Parícutin about 1 kilometer south of Loma Larga; 47.7 percent solids by volume.

W–5. Very heavily laden flow of stream, about 1 meter wide, 1 kilometer west of Llanos de La Caja; 78.4 percent solids by volume.

W–6. Material from bottom end of mudflow that had come to rest 10 minutes before near Cerro de Canicjuata; 91.1 percent solids by volume.

W–7. Flood sample from Arroyo de Corucjuata, near Sinámichu; 58.8 percent solids by volume.

W–8. Material from tiny rill in flood from top of Cerro de La Máscara; 51.6 percent solids by volume.

W–9. Flood sample from barranca that heads on north face of Cerro de La Máscara; 38.6 percent solids by volume.

W–10. Flood sample from Barranca de Queréndaro near Zirosto; 30.1 percent solids by volume.

W–11. Flood sample from Río de Itzícuaro near Zirosto; 78.8 percent solids by volume.

W–12. Flood sample from Río de Itzícuaro, 1 kilometer east of San Francisco; 57.0 percent solids by volume.

W–14. Flood sample from Llano Grande; 4.9 percent solids by volume.

W–15. Sample of normal flow from Río de Itzícuaro at site of sample W–12; 2.1 percent solids by volume.

W–22. Flood sample from Barranca de Huachángueran; 57.9 percent solids by volume.

W–24. Ooze on channel floor of Río de Itzícuaro just below junction with Arroyo de Corucjuata and Arroyo de Huirambosta; 77.6 percent solids by volume.

W–27. Sample from front end of moving mudflow on ridge between Canicjuata and Corucjuata; 94.7 percent solids by volume.

W–29. Flood sample from Río de Itzícuaro just below junction with Arroyo de Corucjuata and Arroyo de Huirambosta, near site of sample W–24; 72.2 percent solids by volume.

W–30. Flood sample from Arroyo de Huirambosta near site of sample W–29; 37.8 percent solids by volume.

W–31. Flood sample from Arroyo de Corucjuata near site of sample W–29; 88.0 percent solids by volume.

W–32. Flood sample from Río de Itzícuaro at brink of falls above junction with Barranca de Tiripan; 88.9 percent solids by volume.

GEOGRAPHIC FEATURES IN THE PARICUTIN REGION, MICHOACAN, MEXICO

By Carl Fries, Jr.

The great majority of geographic names in the Parícutin region are Spanish-language adaptations of Tarascan words. Inasmuch as the Tarascan tongue uses several consonants and one vowel foreign to Spanish, most of the adaptations can only approximate the sound of spoken Tarascan. This has led to much confusion in the spelling of place names, to the extent that a single name may have four different spellings, which may lead one to think that each represents a different feature. In order to clarify this confusion for the reader, the following list has been prepared. The description and location of the features are given only in conjunction with the preferred spelling of each name. Some names that do not appear in the present text are included because they occur in other published reports on the Parícutin region.

To indicate the difficulty in transliterating from the written Tarascan to a pronounceable Spanish and yet maintaining some phonetic resemblance to the original, the following example may be of interest: *Cheranástico* (Spanish adaptation)=*ch'eráni jájtsakuɹini* (written Tarascan). It will be noted that the final ending (*ɹini*) of the Tarascan name is dropped in the Spanish adaptation—a common practice that probably derives from the spoken Tarascan, for the endings are barely audible to the listener (or are even dropped) and are not recognized by one who is unfamiliar with the tongue.

In preparing the list, it was decided to use the spellings of all the names that appear in the Mexican Government census for 1940. For local names of hills and arroyos that are not included in the official census, spellings were chosen that would conform most nearly to the sound of the spoken word in the Parícutin region, using the Spanish alphabet and its phonetic values. Sr. Celedonio Gutiérrez and two friends of his who are native to the region were of great help in defining the terms, and Maxwell D. Lathrop, a student of the Tarascan language who has lived in Cherán for some years, aided in determining the appropriate Spanish transliteration.

There has been, and continues to be, much confusion in transliterating the phonetic value of *s*, which in Spanish may be changed to *c*, *s*, or *z* without any apparent reason for using one or another of these letters. The same holds true for the phonetic value of *ts*, which may be written in Spanish as *c*, *z*, *tz*, or even *ts*. When any choice could be

859358—50——11

made, the *s* sound was designated by *s* and the *ts* sound by *ts*, but in general these phonetic values have been transliterated by other writers as *z* and *tz*. A sound that is foreign to Spanish but is represented in English by *sh* occurs in many words and has been transliterated generally as *ch* or *x*. Wherever the latter letter appears, it carries the phonetic value of *sh* in English, but one cannot be sure of the proper phonetic value of *ch*.

With these few hints, and by following the ordinary rules of pronunciation and accentuation of the Spanish language, the names given in the following list can be pronounced with a fair approximation of the Tarascan.

Agua, Cerro del. See **Terutsjuata, Cerro de.**
Agua Blanca. Village on road to Tancítaro, 20 kilometers S. 60° W. of Uruapan.
Agua Blanca, Río del. River 15 kilometers N. 75° S. of Parícutin volcano.
Aguacate, El. Dam site 3 kilometers south-southeast of Los Reyes.
Aguacate, Llano del. Plain bordering Río de Itzícuaro.
Aguán. See **Ahuán.**
Aguila, Cerro del. Old volcano halfway between Paracho and Capacuaro.
Ahuán. Name assigned to intermittent lava vent at south-southwest base of Parícutin volcano.
Aire, Cerro del. Complex cone 4 kilometers S. 20° W. of Capacuaro.
Alberca, La. Closed depression 1.5 kilometers northeast of Volcán de Jorullo.
Alberca, Cerro de La. Applied to two features: a cone 19 kilometers S. 15° W. of Parícutin volcano and a cone 17 kilometers S. 70° E. of Parícutin volcano.
Alberquita, La. Valley 1 kilometer east of Volcán de Jorullo.
Alto, Torreo El. See **Torreo El Alto.**
Amoles, Cerro de Los. Cone 7 kilometers S. 65° E. of San Felipe.
Angahua. See **Angahuan.**
Angahuan. Village 7 kilometers N. 30° E. of Parícutin volcano.
Angahuan, Cerros de. Large mountain mass to the northeast of Angahuan. Not to be confused with Cerro de Terutsjuata, the small cone at the immediate north edge of Angahuan.
Anillo, El. See **Anillo, Cerro del.**
Anillo, Cerro del. Small breached cone 8 kilometers N. 10° W. of Parícutin volcano.
Apatzingán. Town about 50 kilometers southwest of Uruapan.
Apo. Village 20 kilometers S. 70° W. of Parícutin volcano.
Apucha, Cerro de. Hill 4 kilometers north of Barranca Seca.
Apupan, Cerro de. Cone 12 kilometers N. 60° E. of Parícutin volcano.
Arantepacua. Village about 38 kilometers N. 75° E. of Parícutin volcano.
Aranza. Village 3 kilometers northeast of Paracho.
Araparícuaro. Village 24 kilometers S. 10° W. of Parícutin volcano.
Arátiro, Cerro de. See **Jarátiro, Cerro de.**
Atrozada, Cuchilla. See **Cuchilla Atrozada.**
Axuno, Llano de. Small plain 2 kilometers east of San Juan Parangaricutiro.

Balsas, Río de Las. Main river between Parícutin region and Pacific coast. Río de Itzícuaro and Río de Cupatitzio are tributary to Río de Tepalcatepec, which is in turn tributary to Río de Las Balsas.
Barranca Puerca. Gully near south base of Volcán de Jorullo.

Barranca Seca. Village 13 kilometers N. 60° W. of Parícutin volcano.
Barrancas, Las. Village on road to Tancítaro, 24 kilometers S. 60° W. of Uruapan.
Barranco, Río del. Tributary to Río de Cupatitzio near Jicalán.
Bermúdez, Llanos de. Small plains 3 to 4 kilometers southwest of Zirosto.
Blanca, Agua. See **Agua Blanca.**
Blanca, Río del Agua. See **Agua Blanca, Río del.**

Caja, Llanos de La. Small plains 2.5 kilometers southwest of Parícutin volcano.
Caltzontzin. New village 7 kilometers east of Uruapan where evacuees of Parícutin village were resettled in 1943.
Caltzonzin. See **Caltzontzin.**
Calzontzin. See **Caltzontzin.**
Calzonzin. See **Caltzontzin.**
Camiro, Cerro de. Cone 4 kilometers south of Parícutin volcano.
Canicjuata, Cerro de. Cone 2 kilometers west of Parícutin volcano.
Caniguata, Cerro de. See **Canicjuata, Cerro de.**
Canijuata, Cerro de. See **Canicjuata, Cerro de.**
Cantera, Cerro de La. Cone 4 kilometers south of Parícutin volcano.
Cantera, Rancho de La. Farm on eastern part of Mesa de Huanárucua.
Cantero, Llano del. Plain 5.5 kilometers south of Parícutin volcano.
Capacuaro. Village 26 kilometers N. 75° E. of Parícutin volcano.
Capacuaro, Cerros de. Large mountain 7 kilometers east of Capacuaro.
Capágnito, Lomas de. See **Capánguito, Lomas de.**
Capánguito, Lomas de. Locality 5 kilometers N. 60° E. of Parícutin volcano.
Capánito, Lomas de. See **Capánguito, Lomas de.**
Capáñito, Lomas de. See **Capánguito, Lomas de.**
Capatacutiro, Cerro de. Cone 7 kilometers N. 20° W. of Capacuaro.
Capatzin, Cerro de. See **Capatzun, Cerro de.**
Capatzun, Cerro de. Hill 4 kilometers N. 15° E. of Parícutin volcano.
Carapan. Village at junction of Uruapan and Mexico-Guadalajara highways. Not to be confused with Charapan.
Cátacu, Cerro de. Cone 5 kilometers S. 50° W. of Parícutin volcano.
Cazuela, Olla y. See **Ollicazuela.**
Cebolla, Cerro de La. Hill about 5 kilometers northeast of Peña del Horno.
Ceboruco, Volcán de. Historically active volcano 130 kilometers west-northwest of Guadalajara.
Cerro Cojti. Crater 4 kilometers north of Uruapan.
Cerro Colorado. Mountain 10 kilometers east of Uruapan.
Cerro Costo. See **Cerro Cojti.**
Cerro Pelón. Cone 2 kilometers north of Paracho.
Cerro Prieto. Cone 7 kilometers S. 25° E. of Parícutin volcano.
Cerundan, Cerro de. See **Surúndaro, Cerro de.**
Charanda, Cerro de. Hill 3 kilometers north of Uruapan.
Charapan. Village about 20 kilometers north of Parícutin volcano. Not to be confused with Carapan.
Cheranguerán, Cerro de. Cone 7 kilometers north of Uruapan.
Cheringerán, Cerro de. See **Cheranguerán, Cerro de.**
Chico, Pueblo. See **Pueblo Chico.**
Chino, Cerro del. Hill 4 kilometers west of Uruapan.
Chivo, Río del. River 25 kilometers S. 25° W. of Parícutin volcano.
Chondo, Río de. See **Xundan, Río de.**
Chórotiro, Llano de. Plain at edge of new lava, 5 kilometers N. 45° E. of Parícutin volcano.

Chuánitu, Barranca de. Stream flowing west from Cerro de La Máscara.
Cinzungo, Cerro de. See **Tzintzungo, Cerro de.**
Cirimundiro, Mesa de. See **Zirimóndiro, Mesa de.**
Cocjarao, Mesa de. Locality 2 kilometers southwest of Parícutin volcano.
Codémbaro, Rancho de. Settlement 25 kilometers S. 20° W. of Parícutin volcano.
Cofradía, Hacienda de La. Ranch 3.5 kilometers south-southeast of Los Reyes.
Cojti, Cerro. See **Cerro Cojti.**
Colchas, San Juan de Las. See **San Juan Parangaricutiro.**
Colorada, Loma. See **Loma Colorada.**
Colorado, Cerro. See **Cerro Colorado.**
Condembaro, Rancho de. See **Codémbaro, Rancho de.**
Conejos, Los. New village 19 kilometers S. 45° E. of Parícutin volcano to which evacuees of San Juan Parangaricutiro moved in 1944.
Conejos, Río de Los. Tributary to Río de Cupatitzio near Zumpinito.
Conejos, San Juan de Los. See **Conejos, Los.**
Conijuata, Cerro de. See **Canicjuata, Cerro de.**
Cópetiro, Cerro de. See **Cópitiro, Cerro de.**
Copitero, Cerro de. See **Cópitiro, Cerro de.**
Cópitiro, Cerro de. Cone 10 kilometers N. 10° E. of Uruapan.
Coronilla, La. Feature on rim of Volcán de Ceboruco.
Corucjuata, Cerro de. Cone 4 kilometers N. 50° W. of Parícutin volcano.
Coruguata, Cerro de. See **Corucjuata, Cerro de.**
Corujuata, Cerro de. See **Corucjuata, Cerro de.**
Corupichu, Cerro de. See **Curupichu, Cerro de.**
Corupo. Village 15 kilometers north of Parícutin volcano.
Costo, Cerro. See **Cerro Cojti.**
Coyotes, Mesa de Los. Lava plain northwest of Volcán de Jorullo.
Cruces, Puerto de Las. Pass between San Lorenzo and Angahuan.
Cruz, Cerro de La. Mountain 5 kilometers N. 20° E. of Uruapan.
Cuatzione, Cerro de. Cone in cluster near San Lorenzo.
Cuauchándaran, Cerro de. See **Cuaxándaran, Cerro de.**
Cuaxándaran, Cerro de. Cone 5 kilometers N. 70° W. of Parícutin volcano.
Cuchilla Atrozada. Hill 1.5 kilometers northwest of Volcán de Jorullo.
Cuezeño. Locality 5 kilometers N. 5° E. of Parícutin volcano, where "lower casitas" are situated.
Cuiyúsuru, Llano de. Field in which Parícutin volcano broke out.
Cuiyutziro, Llano de. See **Cuiyúsuru, Llano de.**
Cumbuén, Cerro de. Cone pair 1 kilometer northwest of Paracho.
Cumbundacato, Cerro de. See **Cumbundicato, Cerro de.**
Cumbundicato, Cerro de. Young cone on west flank of Cerros de Angahuan.
Cupatitzeo, Río de. See **Cupatitzio, Río de.**
Cupatitzio, Río de. Tributary to Río de Tepalcatepec, rising at Uruapan.
Curicerán, Cerro de. See **Curitzerán, Cerro de.**
Curínguaro. Locality 3 kilometers east of Parícutin volcano.
Curíngüaro. See **Curínguaro.**
Curitzerán, Cerro de. Cone pair 8 kilometers N. 10° W. of Parícutin volcano.
Curupichu, Cerro de. Cone pair 5 kilometers east of Parícutin volcano.
Cutzato, Cerro de. Large cone 7 kilometers N. 85° E. of Parícutin volcano.
Cuzato, Cerro de. See **Cutzato, Cerro de.**
Cuzeño. See **Cuezeño.**

Elóndima, Cerro de. See **Ondiman, Cerro del.**

Enmedio, Volcancito de. Satellite cone 1 kilometer southwest of Volcán de Jorullo.
Equijuata, Cerro de. Hill 3 kilometers N. 30° E. of Parícutin volcano.
Escondida, Rancho de La. Ranch 2 kilometers southwest of Volcán de Jorullo.
Escondido, El. Village 2 kilometers north of Apo.

Fresno, Río del. River 20 kilometers south of Parícutin volcano.

Gachupín, Cerro del. Hill 2.5 kilometers north of Barranca Seca.
Gallinero, Cerro del. Hill 4 kilometers north-northwest of Angahuan.
Grande, Llano. See **Llano Grande.**
Guanárucua, Mesa de. See **Huanárucua, Mesa de.**
Guarnáracua, Mesa de. See **Huanárucua, Mesa de.**
Guatarillo, El. See **Huatarillo, El.**

Hornitos, Mesa de Los. Mesa formed by new lava at southwest base of Parícutin volcano during 1944.
Horno, El. See **Horno, Peña del.**
Horno, Peña del. Prominent rock mass on north flank of Cerros de Tancítaro, 8 kilometers S. 40° W. of Parícutin volcano.
Horno de Tancítaro, El. See **Horno, Peña del.**
Hornos, Cerros de Los. Mountain of several cones 4 kilometers north of San Lorenzo.
Huanárucua, Mesa de. Mesa 7 kilometers north of Parícutin volcano.
Huatarillo, El. Village in municipality of Peribán.
Huhirambosta, Llano de. See **Huirambosta, Llano de.**
Huirambosta, Barranca de. Gully near Llano de Huirambosta.
Huirambosta, Llano de. Plain 5 kilometers N. 40° W. of Parícutin volcano.
Hurengo, Barranca de. See **Urengo, Barranca de.**
Hurítzicuaro, Cerro de. See **Jurítzicuaro, Cerro de.**

Imbarácuaro. Narrow gorge of Río de Itzícuaro about 7 kilometers east of Los Reyes.
Itzícuaro, Planta de. Power plant 4.5 kilometers east of Los Reyes.
Itzícuaro, Río de. River heading near Zirosto, 10 kilometers N. 60° W. of Parícutin volcano, tributary to Río de Tepalcatepec.

Jabalí, Cerros del. Cone cluster 7 kilometers northwest of Uruapan.
Jarátiro, Cerro de. Hill 2.5 kilometers north of Parícutin volcano, where "upper casitas" observatories are located.
Jicalán. Village at base of Cerro de Jicalán, 4 kilometers S. 15° W. of Uruapan.
Jicalán, Cerro de. Cone 4 kilometers S. 20° W. of Uruapan.
Jorullo, Volcán de. Historically active volcano about 75 kilometers southwest of Parícutin volcano.
Juatito. Lava vent at northeast base of Parícutin volcano.
Jucutacato. Village 6 kilometers S. 20° W. of Uruapan.
Jurítzicuaro, Cerro de. Cone 6.5 kilometers S. 50° E. of Parícutin volcano.

Lagunita, La. Depressed area 2 kilometers east of Parícutin volcano, now covered by lava.
Larga, Loma. See **Loma Larga.**
Limones, Presa de Los. Dam on Río de Itzícuaro 3 kilometers southwest of Los Reyes.

Llano Grande. Plain extending northwest from San Juan Parangaricutiro, 6 kilometers north of Parícutin volcano.
Lobos, Los. Village 17 kilometers S. 80° W. of Uruapan.
Loma Colorada. Cone 5 kilometers S. 65° E. of San Felipe.
Loma Larga. Young cone 1 kilometer west-southwest of Cerro de Canicjuata, 2 kilometers west of Parícutin volcano.
Lopezio, Cerro de. See **Lópizio, Cerro de.**
Lópizio, Cerro de. Cone 4.5 kilometers south of Parícutin volcano.

Magdalena, Bolita de. Low ridge 4 kilometers south of Uruapan.
Máscara, Cerro de La. Old cone 8 kilometers N. 85° E. of Parícutin volcano.
Matáncero, Cerro de. Small cone 11 kilometers N. 60° E. of Parícutin volcano.
Mechicano. See **Mexicano.**
Mexicano. Locality 3 kilometers east of Parícutin volcano.

Noreto, Arroyo de. See **Nureto, Arroyo de.**
Noreto, Cerro de. See **Nureto, Cerro de.**
Norte, Volcancito del. Satellite cone 2 kilometers northeast of Volcán de Jorullo.
Nuréndiro, Cerro de. Hill 1.5 kilometers south of Parícutin volcano. At base of hill is a spring, now deeply buried by ash.
Nureto, Arroyo de. Stream 6 kilometers N. 40° E. of Parícutin volcano.
Nureto, Cerro de. Cone 7 kilometers N. 45° E. of Parícutin volcano.
Nurío. Village 8 kilometers west-southwest of Paracho.
Nurío, Cerro de. Hill near Nurío.

Obispo, El. Triangulation station 1 kilometer east of Cuezeño.
Olla, Cerro de La. See **Purechjuata, Cerro de.**
Olla y Cazuela. See **Ollicazuela.**
Ollicazuela. Locality halfway between Apo and Peribán.
Ollicazuela, Barranca de. Stream heading 5 kilometers west of Peña del Horno.
Ondiman, Cerro del. Cone 8 kilometers east of San Felipe.
Otates, Cerro de Los. Hill 3 kilometers northwest of Zacán.

Pancingo, Cerro de. See **Pantzingo, Cerro de.**
Pantzingo, Cerro de. Small cone at southwest base of Cerro de Cutzato, 4.5 kilometers N. 85° E. of Parícutin volcano.
Panzingo, Cerro de. See **Pantzingo, Cerro de.**
Paquichu, Llano de. Plain north of Mesa de Huanárucua.
Paracho. Village 32 kilometers N. 55° W. of Parícutin volcano.
Paracho, Cerros de. Mountain mass to southeast of Paracho.
Paracho Viejo, Cerro de. Cone 3 kilometers west of Paracho.
Paracutan. See **Parícutin.**
Parangaricutiro, San Juan. See **San Juan Parangaricutiro.**
Parástaco, Cerro de. Hill on northwest flank of Cerros de Tancítaro, 11 kilometers S. 65° W. of Parícutin volcano and 12 kilometers southeast of Peribán.
Parastago, Cerro de. See **Parástaco, Cerro de.**
Parícuti. See **Parícutin.**
Parícutin. Village, now buried by lava, 2.5 kilometers N. 30° W. of Parícutin volcano and from which the volcano derives its name. In the Tarascan language the word is written *Paɹikutini* and means "the locality on the other side of the gully or arroyo." The name is common in the region and is used for settlements that are located across arroyos from larger towns, as at Cherán, a village to the northeast of Aranza, where there is also a Parícutin.

Parícutin, Volcán de. Volcano that broke out on February 20, 1943, in a field about 16 kilometers northwest of Uruapan and whose name comes from that of the nearest village. In the present report, unless otherwise specified, the name Parícutin alone is understood to refer to the volcano.

Pario, Cerro de. Cone 8 kilometers S. 70° E. of Parícutin volcano.

Pechu, Llano de. Small plain about 2 kilometers east-northeast of Peña del Horno.

Pelón, Cerro. See **Cerro Pelón.**

Peña del Horno. See **Horno, Peña del.**

Peribán. Village 20 kilometers N. 80° W. of Parícutin volcano.

Pirámides, Las. Pyramidlike hills extending north from Parícutin volcano, formed in 1943 by lava rafting of parts of the cone and by sill-like injections of lava beneath the solidified crust of earlier lava. These hills were buried by lava during 1947 and 1948.

Pomacuarán, Ojo de. Spring in arroyo 5.5 kilometers N. 15° W. of Parícutin volcano.

Prieto, Cerro. See **Cerro Prieto.**

Pueblo Chico. Locality on northeast flank of Cerros de Tancítaro, about 4 kilometers S. 35° W. of Parícutin volcano.

Pueblo Viejo, Cerro del. Cone 5 kilometers N. 85° W. of Parícutin volcano.

Puerca, Barranca. See **Barranca Puerca.**

Puerto, Cerro del. Cone 9 kilometers N. 25° E. of Uruapan.

Purechjuata, Cerro de. Cone 8 kilometers S. 50° E. of Parícutin volcano.

Purísima, Cerro de La. Highest peak of Cerros de Angahuan, 11 kilometers N. 40° E. of Parícutin volcano.

Querendacahuaro, Barranca de. Stream heading 5 kilometers east of Angahuan.

Queréndaro, Barranca de. Gully 5 kilometers west of Parícutin volcano.

Queyuréndiro, Barranca de. See **Queréndaro, Barranca de.**

Quitzocho, Llano de. Field a few hundred meters from site of eruption of Parícutin volcano.

Quizotcho, Llano de. See **Quitzocho, Llano de.**

Reyes, Los. Town 24 kilometers west-northwest of Parícutin volcano.

San Antonio, Río de. River 7 kilometers south-southeast of Uruapan.

San Felipe. Village 19 kilometers N. 40° W. of Parícutin volcano.

San Francisco. Village 15 kilometers northwest of Parícutin volcano.

San José. Village 3 kilometers north of Barranca Seca.

San Juan. See **San Juan Parangaricutiro.**

San Juan de Las Colchas. See **San Juan Parangaricutiro.**

San Juan de Los Conejos. See **Conejos, Los.**

San Juan Nuevo. See **Conejos, Los.**

San Juan Parangaricutiro. Town 5 kilometers north of Parícutin volcano, partly buried by lava flows in 1944 and 1945.

San Lorenzo. Village 20 kilometers N. 80° E. of Parícutin volcano.

San Lorenzo, Barranca de. Tributary of Río de Cupatitzio north of Uruapan.

San Marcos, Cerros de. Mountain mass 8 kilometers east of Paracho.

San Pedro, Cerro de. Peak on north flank of Cerros de Tancítaro, 7 kilometers S. 40° W. of Parícutin volcano.

San Pedro, Planta de. Power plant in Uruapan.

San Sebastián, Ingenio de. Sugar mill 2.5 kilometers south-southwest of Los Reyes.

San Vicente, Cerro de. Hill 5.5 kilometers east of Peña del Horno.

Santa Catarina. Locality on road to Tancítaro, 20 kilometers S. 65° W. of Uruapan.

Sapichu. Parasitic cone on northeast flank of Parícutin volcano, active in 1943 but later buried.

Sapien, Cerro de. Easternmost cone of Jabalí cluster, 7 kilometers northwest of Uruapan.

Seca, Barranca. See **Barranca Seca.**

Sicapen, Cerro de. Cone 10 kilometers S. 40° W. of Paracho.

Sicuín, Cerro de. Cone 6.5 kilometers N. 30° W. of Parícutin volcano.

Sinámichu, Cerro de. Hill 4 kilometers N. 45° W. of Parícutin volcano.

Sipicha. Springs 1 kilometer north of Zirosto, headwaters of Río de Itzícuaro.

Sur, Volcancito del. Satellite cone 1.5 kilometers southwest of Volcán de Jorullo.

Surúndaro, Cerro de. Cone 14 kilometers N. 60° W. of Parícutin volcano.

Tancítaro. Village 25 kilometers S. 40° W. of Parícutin volcano.

Tancítaro, Cerros de. Large mountain mass on whose northeast flank Parícutin volcano is located.

Tancítaro, Horno de. See **Horno, El.**

Tancítaro, Pico de. Highest peak on Cerros de Tancítaro.

Tecatas, Cerro de Las. See **Tecates, Cerro de Los.**

Tecates, Cerro de Los. Hill adjacent to Cerro de Las Ventanas.

Tejamanil, El. Village about 25 kilometers S. 80° W. of Uruapan, 16 kilometers south of Parícutin volcano.

Tepalcatepec, Río de. River located south of Parícutin region, tributary to Río de las Balsas.

Teporícuaro, Ojo de. Spring near Corupo.

Terajuata, Cerro de. See **Turajuata, Cerro de.**

Teruto, Llano de. Plain 4 kilometers S. 30° E. of Parícutin volcano.

Terutsjuata, Cerro de. Cone on north edge of Angahuan.

Terutsjuata, Ojo de. Spring on Cerro de Terutsjuata.

Ticuiro, Arroyo de. Stream about 5 kilometers N. 35° W. of Parícutin volcano.

Tipúracuaro, Llano de. Field near Llano de Cuiyúsuru.

Tipúragüaro, Llano de. See **Tipúracuaro, Llano de.**

Tiripan, Cerro de. Cone 6 kilometers N. 50° W. of Parícutin volcano.

Tisne, Cerro de. Hill 6 kilometers east-northeast of Peña del Horno.

Tizne, Cerro de. See **Tisne, Cerro de.**

Torreo El Alto. Locality 10 kilometers N. 20° E. of Uruapan, east of Cerro de Cópitiro.

Torreo 'Lalto. See **Torreo El Alto.**

Tsaráracua, Cascada de. See **Tzaráracua, Cascada de.**

Tumbiscato, Cerro de. Cone 11 kilometers S. 65° E. of Parícutin volcano.

Turajuata, Cerro de. Cone 3 kilometers N. 85° W. of Parícutin volcano.

Tzaráracua, Cascada de. Waterfalls on Río de Cupatitzio, 9 kilometers south of Uruapan.

Tzintzungo, Cerro de. Cone 7 kilometers N. 30° E. of Parícutin volcano.

Tzirapan, Cerro de. Cone 3 kilometers S. 50° E. of Parícutin volcano.

Urengo, Barranca de. Gully 5.5 kilometers north of Parícutin volcano.

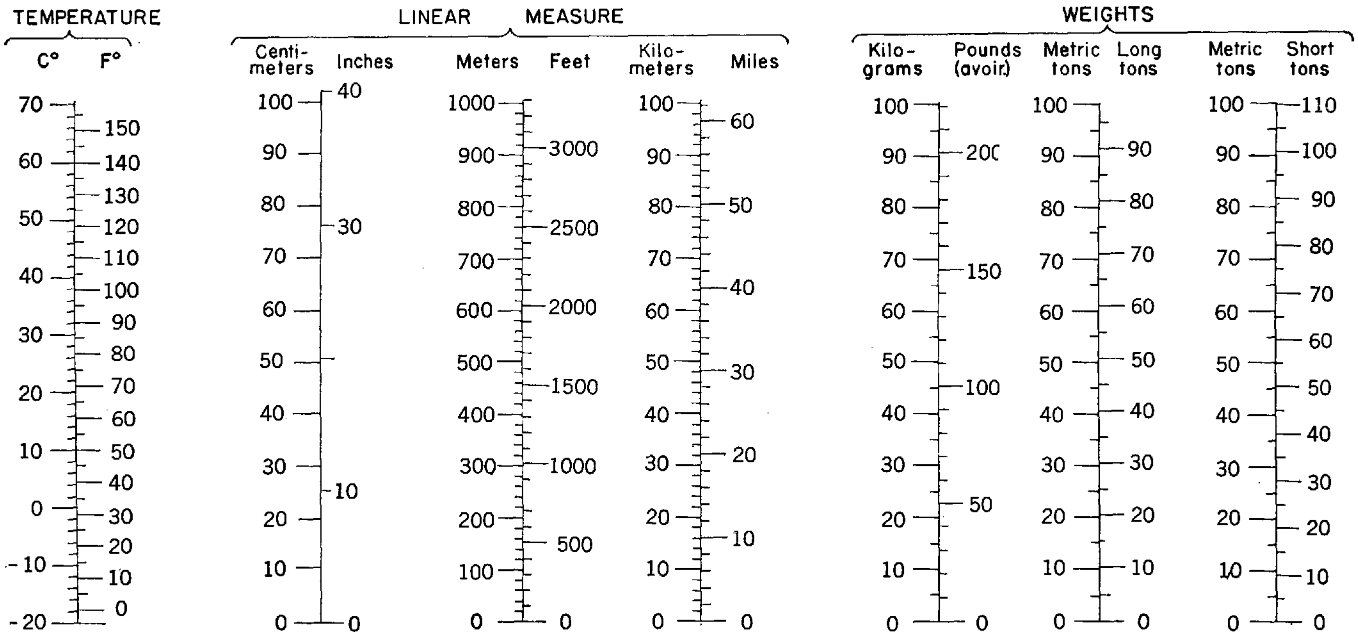
Uruapan. City 26 kilometers S. 65° E. of Parícutin volcano.

Ventanas, Cerro de Las. Mountain 10 kilometers south-southeast of Uruapan.
Vermúdez, Llanos de. See **Bermúdez, Llanos de.**
Viejo, Cerro de Paracho. See **Paracho Viejo, Cerro de.**
Viejo, Cerro del Pueblo. See **Pueblo Viejo, Cerro del.**

Xundan, Río de. Tributary to Río de Itzícuaro near Peribán.

Zacán. Village 10 kilometers N. 30° W. of Parícutin volcano.
Zacán, Cerro de. Hill just west of Zacán.
Zacán, Ojo de. Spring on Cerro de Zacán.
Zapicho. See **Sapichu.**
Zapichu. See **Sapichu.**
Zapien, Cerro de. See **Sapien, Cerro de.**
Zicapen, Cerro de. See **Sicapen, Cerro de.**
Zicuín, Cerro de. See **Sicuín, Cerro de.**
Zinámichu, Cerro de. See **Sinámichu, Cerro de.**
Zipicha. See **Sipicha.**
Zirapa, Cerro de. See **Tzirapan, Cerro de.**
Zirapan, Cerro de. See **Tzirapan, Cerro de.**
Zirimo, Barranca del. Long stream heading just south of Cutzato.
Zirimóndiro, Mesa de. Mesa 3 kilometers north of Tancítaro.
Zirosto. Village 10 kilometers N. 60° W. of Parícutin volcano.
Zirosto, Cerros de. Group of cones, including Cerro de La Máscara, 9.5 kilometers N. 80° W. of Parícutin volcano.
Zumpimito. See **Zumpinito.**
Zumpinito. Hydroelectric plant 8 kilometers south of Uruapan on Río de Cupatitzio.
Zumpinuto. See **Zumpinito.**

METRIC EQUIVALENTS



1 cm. = 0.3937 in.
1 in. = 2.5400 cm.

1 m. = 3.2808 ft.
1 ft. = 0.3048 m.

1 km. = 0.6214 mile
1 mile = 1.6093 km.

1 sq. m. (m2) = 1.20 sq. yd.
1 hectare (100x100m.) = 2.47 acres
1 cu. m. (m3) = 1.31 cu. yd.

1 kg. = 2.2046 lb.
1 lb. = 0.4536 kg.

1 metric ton = 0.9842 long ton
1 metric ton = 1.1023 short tons
1 metric ton = 2,205 lb.
1 long ton = 1.0161 metric ton
1 short ton = 0.9072 metric ton

INDEX

Volcanoes of the Parícutin Region Mexico

By HOWEL WILLIAMS

GEOLOGIC INVESTIGATIONS IN THE PARICUTIN AREA, MEXICO

GEOLOGICAL SURVEY BULLETIN 965-B

Prepared in cooperation with the Secretaría de la Economía Nacional de México, Dirección de Minas y Petróleo, and the Universidad Nacional Autónoma de México, Instituto de Geología, under the auspices of the Interdepartmental Committee on Scientific and Cultural Cooperation, Department of State

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1950

UNITED STATES DEPARTMENT OF THE INTERIOR

Oscar L. Chapman, *Secretary*

GEOLOGICAL SURVEY

W. E. Wrather, *Director*

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C. - Price 65 (paper cover)

CONTENTS

ILLUSTRATIONS

TABLES

VOLCANOES OF THE PARICUTIN REGION

By Howel Williams

ABSTRACT

The oldest bedded rocks in the Parícutin region comprise the Zumpinito formation, presumably of early Tertiary age. They consist of andesitic lavas, mudflow breccias, tuffs, and tuffaceous sediments, with subordinate sheets of welded rhyolite tuff, olivine basalt, and hornblende andesite that lie horizontally or almost so. Probably they underlie Parícutin volcano at a shallow depth.

Near Uruapan, the Zumpinito beds are closely associated with coarse-grained gabbros of uncertain age, which are probably coeval with the quartz monzonites found among the ejecta of the new volcano.

Following a long period of erosion, the huge volcanoes of Cerros de Tancítaro and Cerros de San Marcos were built to the southwest and northeast, respectively, of Parícutin by quiet effusions of pyroxene andesite. Shortly thereafter the andesitic volcanoes of Cerro del Aguila and Cerros de Angahuan were developed. The adjacent volcanoes forming Cerros de Los Hornos, which may have originated at the same time, continued to be active to a later date, building an overlapping group of cones of basalt and basaltic andesite. All these post-Zumpinito volcanoes are considerably eroded and, for that reason, are considered to be of late Pliocene or early Pleistocene age.

During the remainder of Pleistocene time, and subsequently, scores of large lava cones and hundreds of smaller cinder cones rose to dominate the landscape of Michoacán. Most of these erupted olivine basalt and olivine-bearing basaltic andesite, but many volcanoes and several isolated flows discharged during the last few thousand years consist of pyroxene andesite. No regular trend of differentiation has been detected.

The lavas now being emitted by Parícutin are olivine-bearing basaltic andesites essentially similar to the majority of the late Pleistocene and Recent flows of the region. Most of the young volcanoes are arranged without order; a few are alined northeast-southwest, parallel to the principal fissure zone at the new volcano.

INTRODUCTION

SCOPE OF WORK

On February 20, 1943, a new volcano burst into activity in the State of Michoacán, Mexico, approximately 65 miles northwest of Jorullo, the volcano born in 1759. The new volcano aroused widespread interest, and many geologists, both from Mexico and the United States, hastened to examine its activity. Particularly important has been the work of the late Ezequiel Ordóñez, dean of Mexican geologists, who first visited the volcano a few days after its birth and then returned at short intervals to observe its behavior. During the first 2 years the volcano was also studied closely by Jenaro González R., of the Instituto de Geología, and by W. F. Foshag, then a member of the United States Geological Survey.

In 1944 the National Research Council appointed a "United States Committee for the Study of Parícutin Volcano" under the chairmanship of R. E. Fuller to work in cooperation with a Mexican committee appointed by the Comisión Impulsora y Coordinadora de la Investigación Científica in order to stimulate, guide, and facilitate a program of research. In November of that year, through the financial support of the State Department's Interdepartmental Committee on Scientific and Cultural Cooperation, the writer was sent by the United States Geological Survey to prepare a reconnaissance map and report covering an area of about 600 square miles around the new volcano with the object of determining its relations to neighboring cones. The present paper embodies the chief results of that work. After laboratory examination of collections made between November 1944 and May 1945, the writer revisited the region during 5 weeks in July and August 1947, aided by grants from the Geological Society of America and the Board of Research of the University of California.

Geological boundaries were plotted on aerial photographs made in 1934 by the Compañía Mexicana Aerofoto. Unfortunately no topographic base has been compiled from these pictures; hence the geological map reproduced here as plate 8 is only approximately correct. Nevertheless, for the purpose in mind, the photographs sufficed. In May 1945, additional pictures were taken, by the same agency, of the area immediately adjacent to the new volcano after Kenneth Segerstrom of the United States Geological Survey had prepared a ground control.

By November 1944, when the present survey began, the region close to Parícutin was already so heavily blanketed by newly fallen ash that it proved impossible to make an accurate geological map. It can only be hoped that this critical area will be restudied when the cover of ash has been largely removed by erosion.

In the pages that follow, no attempt is made to present more than a brief summary of the history of the new volcano. Many published accounts are already available (see "References cited" at the end of this report), and shortly others by Foshag and González R. and by Wilcox may be expected to appear. Nor has any attempt been made to describe in detail the petrographic character of the Parícutin lavas and fragmental ejecta. Enough information is included, however, to indicate the principal features of the lavas and to show how they compare with earlier volcanic rocks in the vicinity.

ACKNOWLEDGMENTS

It is a pleasure to thank Ing. Adán Pérez Peña, of the Instituto de Geología of the University of Mexico, for his pleasant companionship and willing aid during the field work of 1944–45. The writer is also happy to express his gratitude to the late Ing. Ordóñez for many stimulating discussions and welcome advice. Among the geologists and geophysicists who visited the volcano during the writer's stay, the following contributed in various ways to the progress of the work: Virgil Barnes, P. E. Cloud, W. F. Foshag, R. E. Fuller, Jenaro González R., A. E. Jones, Fred Keller, Fred Romberg, Eduardo Schmitter, F. G. Wells, R. E. Wilcox, and E. G. Zies. To Dr. Fuller especial thanks are due for his aid as chairman of the United States Committee for the Study of Parícutin Volcano. All who have worked at the volcano under the auspices of that body will realize the benefits of his helpful counsel. The faithful and friendly aid given by Celedonio Gutiérrez cannot be properly expressed in words, but those who have had the good fortune to share his company will know how much the study of the volcano has been advanced both by his own careful observations and by the unstinted support that he has given to others. To Konrad Krauskopf, the writer is grateful for collections of specimens supplementing his own. Prof. F. J. Turner made several universal-stage measurements and assisted with advice on optical procedures. Finally, the Council of the Geological Society of America made funds available for the preparation of 18 new rock analyses.

LOCATION AND TOPOGRAPHY OF AREA STUDIED

The region to be described lies near the southern edge of the Mexican Plateau, within the Neo-Volcanic Zone where it passes through the western part of the State of Michoacán. It is limited by parallels 19°21′ and 19°37′ N. and meridians 102°2′ and 102°22′ W., and covers approximately 600 square miles.

The new volcano lies near the center of the area, about 200 miles west of Mexico City and 15 miles west-northwest of Uruapan, the nearest town (fig. 74). By paved highway, the distance between Uruapan and Mexico City is 330 miles; by railroad the distance is even longer. About 12 miles north of Uruapan, a branch road leaves the paved highway to run westward through Angahuan to the edge of the Parícutin lava field near Cuezeño and the buried town of San Juan Parangaricutiro. Only during the dry season, and then only with difficulty, is it possible to continue westward by car from San Juan Parangaricutiro to Peribán and Los Reyes. From Angahuan another road runs northward to Corupo and thence via San Felipe to rejoin the main highway

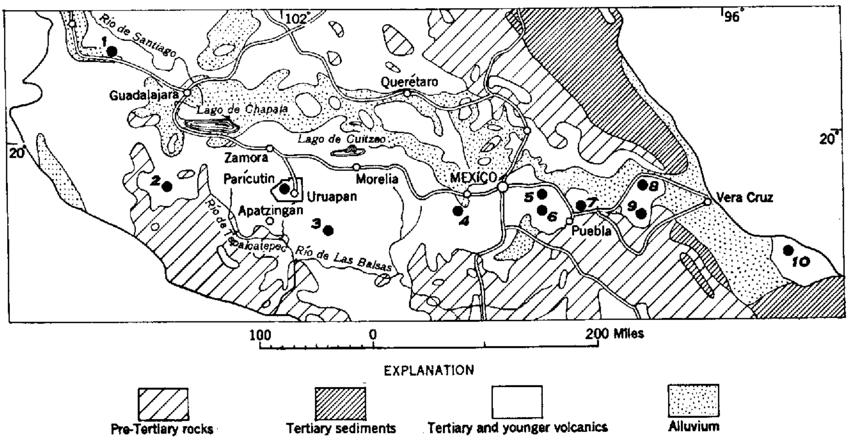


FIGURE 74.—Sketch map of central Mexico, showing location of area studied. Some of the important volcanoes, several of which have erupted in historic times, are indicated by numbers, as follows: (1) Ceboruco, (2) Colima, (3) Jorullo, (4) Nevado de Toluco, (5) Ixtaccíhuatl, (6) Popocatépetl, (7) Malinche, (8) Cofre de Perote, (9) Orizaba, (10) San Andrés Tuxtla. Main highways are shown by double lines. Geological boundaries taken from Geological Map of North America, by G. W. Stose, 1946.

above the village of Capacuaro. Pantzingo, close to the southeast margin of the new lava field, is accessible by a poor truck road that leaves the highway near Cheringerán. Another poor road links Peribán with the villages of Apo and Tancítaro, but it is not recommended for ordinary passenger cars even in the dry season. Buses connect Uruapan with Los Conejos, whence horse trails lead to Tancítaro either through Tejamanil or Las Barrancas.

Parícutin volcano stands in the heart of a country peopled by Tarascan Indians, in a landscape considered by many to be the most beautiful in Mexico. Most of the region is drained westward by the Río de Itzícuaro and its tributaries, which go to feed the Río de Tepalcatepec, itself a branch of the mighty Río de Las Balsas. The remainder of the region is drained southward by springs and streams that swell the Río de Cupatitzio, another feeder of the Río de Las Balsas.

Although satisfactory topographic maps are available only for the immediate vicinity of the new volcano, some idea of the general features of the region may be gained from the sketches and photographs accompanying the present report. In the southern part of the area the land forms are primarily products of erosion; elsewhere the landscape is dominated by volcanic cones. Even the oldest of these still retain slopes that coincide closely with the original surfaces; the youngest are so fresh that they have scarcely been modified by denudation. Within the limits of the geologic reconnaissance map reproduced as plate 8, more than 150 cinder cones and more than 20 large lava cones may be counted, and the mapped area is only part of a vastly larger volcanic field, 500 kilometers long and 100 kilometers wide, extending through the States of México, Michoacán, and Jalisco. As Graton (1945a) has remarked, "probably nowhere else in the world is there such a great concentration of conspicuous volcanic cones over so large an area * * * and nowhere are the basaltic cones more numerous than in the western half of Michoacán, nor in the immediate environs of Parícutin."

The town of Uruapan stands on the edge of the Tierra Caliente, approximately a mile above sea level. The adjacent plain is deeply incised by the gorge of the Río de Cupatitzio and is flanked on the south and east by hills that rise from a few hundred to more than a thousand feet above the general level. The town of Peribán, in the northwest corner of the area mapped, lies at about the same elevation. Farther west gentle slopes descend to the sugarcane country around Los Reyes at an elevation of approximately 4,200 feet.

By far the greater part of the region, however, stands at much higher levels than those just cited. Northward the region of coffee and banana plantations around Uruapan gives place rapidly to pine-clad hills and mountains. Within 12 miles the highway climbs 2,000 feet. Most of the cultivated valleys between the volcanoes lie above 6,500 feet and below 8,000 feet. Here one finds the principal settlements.

Among the volcanoes themselves, the largest and highest by far is the denuded cone forming Cerros de Tancítaro, the summit of which rises almost to 13,000 feet (3,845 meters), towering a mile above the encircling, younger cones (pl. 8; fig. 75). Next in prominence are the twin volcanoes that make up Cerros de Angahuan (figs. 78, 79), culminating in Cerro de La Purísima at an elevation of approximately 10,800 feet (3,292 meters). Then comes the arresting peak of Cerro del Aguila (fig. 77), which also exceeds 10,000 feet in height. Most of the host of cinder cones that crown the lava-built volcanoes and dot their flanks range from 100 to 1,000 feet in height. Late in 1947, the top of Parícutin itself stood at an elevation of 9,100 feet (2,775 meters); the elevation of the cornfield from which it started was approximately 1,400 feet lower.

Eighty percent of the region around the new volcano is forested, chiefly by pines and oaks. Above 10,000 feet, firs predominate. Prior to the present eruptions, half of the cultivated land was given over to corn; less important crops were wheat and beans. Apples, pears, and other fruit were plentiful. It was a countryside as pleasant as its people.

PREVOLCANIC HISTORY

According to the paleogeographic maps prepared by Kellum (1944), almost all the Neo-Volcanic Zone of Mexico, including the State of

Michoacán, was dry land throughout Permian, Triassic, and Lower Jurassic time. According to Robles (1943), on the other hand, geosynclinal seas covered Michoacán intermittently from the Triassic to nearly the close of Cretaceous time. In Kellum's opinion, a seaway connected the Pacific Ocean via southern Jalisco and southern Michoacán with an enlarged Gulf of Mexico that covered the eastern end of the Neo-Volcanic Zone during Upper Jurassic and Lower Cretaceous time. "Broad warping of the continent in Upper Cretaceous time," says Kellum, "marked the beginning of the Laramide revolution which reached its maximum intensity after Maestrichtian time and continued with decreasing vigor in the early Tertiary." During the Upper Cretaceous epoch the seas that had covered the Parícutin region perhaps from Triassic time, certainly from Upper Jurassic time, were expelled by broad uplifts accompanied by igneous intrusions on a large scale.

No pre-Cretaceous rocks are exposed within or near the area to be described; hence there is an unfortunate lack of information concerning the nature and structure of the prevolcanic bedrock of this part of Michoacán.

THE NEO-VOLCANIC ZONE OF MEXICO

Precisely when volcanic activity began in the Neo-Volcanic Zone is still uncertain. Except in a few areas, there is doubt also concerning the succession of the various types of lava.

Robles (1943) states that the oldest lavas are generally andesites, dacites, and rhyolites of Eocene age, but among these he includes the lavas of Tancítaro, which, as noted below, are very much younger. Resting on the supposedly Eocene flows, according to Robles, are andesites and basalts of Pliocene age; then follow Pleistocene latites, andesites, and basalts and finally olivine basalts of Recent age. De la O. Carreño (1943) presents a slightly different succession, beginning with diabases in the early Cenozoic, followed by propylitized andesites in the Miocene, the andesites and rhyolites in the Pliocene, and lastly Pleistocene and Recent flows of basalt. Agreeing with Ordóñez, he assigns the great cones of Tancítaro, Orizaba, Nevado de Toluca, Nevado de Colima, and Ixtaccíhuatl to the Pliocene epoch.

Robles (1943) cites Ordóñez to the effect that the lavas of Eocene age are mainly hornblende andesites and that the ones of Pliocene age include both hornblende and pyroxene andesites and basalts, whereas the Recent lavas are latites, basaltic andesites, and basalts. In the State of Tlaxcala, according to Blásquez (1946), the first eruptions that followed the emergence of the area from the Cretaceous sea were andesitic, and no basalts were erupted until Pleistocene time.

From the foregoing summary it is apparent that much uncertainty remains concerning the age and sequence of the Tertiary lavas, and until the fossil floras and faunas of the interbedded tuffs are examined, the doubts will not be dispelled. The general impression among Mexican geologists is that the early Tertiary flows are dominantly andesitic and the later ones chiefly basaltic. This may prove to be correct for the Neo-Volcanic Zone as a whole, as it seems to be in Nicaragua, but it is true only in a broad sense of the region around Parícutin.

PREVIOUS WORK ON VOLCANISM IN MICHOACAN

Information relating to the volcanic history of that part of the Neo-Volcanic Zone which crosses Michoacán is particularly scarce. Publication of the results of work done in the southern part of the State by Jenaro González R. will do much to clarify the picture.

Flores (1946) reports that volcanism began in the northeast part of the State with discharge of andesite during the Miocene epoch. Then rhyolites were erupted, and, probably in Quaternary time, these were followed by outflows of basalt.

In eastern Michoacán, Ordóñez (1906) noted that near Lakes Cuitzeo and Pátzcuaro the oldest volcanic rocks are andesites and rhyolites. These include the widespread sheets of welded tuff adjacent to Morelia. Resting on these are young basaltic flows. Between Lake Pátzcuaro and Uruapan, andesites again underlie basalts, and, judging from the schematic profile drawn by Ordóñez, a long interval of erosion preceded the eruption of the younger flows.

Blásquez (1946b), writing of the geology of northern Michoacán, says that volcanism was initiated by the discharge of hornblende andesites during the Miocene epoch. Then followed eruptions of dacite and rhyolite. At the close of the Pliocene and during the Pleistocene epoch, these volcanic rocks were largely buried by copious outpourings of basaltic andesite and basalt.

Robles (1943), in discussing the area immediately south of Uruapan, states that two well-defined horizons are present in the gorge of the Río de Cupatitzio. These rest on a complex igneous basement composed of diorites, monzonites, dacites, latites, and andesites. One horizon is described as essentially "cineritic," deposited by eolian and fluvial action and composed of incoherent igneous materials charged with angular debris of fragmental latite. The other horizon is made up of chaotic deposits laid down by torrential waters and mixed with pyroclastic ejecta. These deposits were considered by Robles to be the products of "turbulent avalanches." No doubt both horizons belong to the Zumpinito formation described in the pages that follow.

Robles assigned them to the Pleistocene epoch despite the fact that he referred to Cerros de Tancítaro as Eocene in age. The present survey shows that Tancítaro was built on the eroded surface of the Zumpinito formation, and since part of its original conical form is still preserved, it cannot date farther back than late Pliocene if indeed it is older than early Pleistocene. Besides, if the Zumpinito formation were actually of Pleistocene age, cones of similar materials should still exist in the vicinity, but there is no trace of the volcanoes from which the bouldery deposits of the Zumpinito were derived. They must first have been leveled by erosion, and then their remnants must have been buried by the cones of Quaternary age that now dominate the Tarascan landscape.

ZUMPINITO FORMATION

GENERAL STATEMENT

Within the area covered by this report, the oldest volcanic rocks are referred to as the Zumpinito formation from their occurrence in magnificent sections near the Zumpinito hydroelectric plant, a few miles south of Uruapan. The formation underlies Uruapan itself and also the adjacent plain, where it is mantled by a veneer of basaltic ash blown from neighboring cinder cones. It is exposed in the gorges of the Río de Cupatitzio and its tributaries, and it forms the conspicuous Cerro de La Cruz on the outskirts of Uruapan, as well as Cerro Colorado and the Cerro de Las Ventanas to the east. The road connecting Uruapan and Apatzingán winds over a mountainous terrain carved in beds of the Zumpinito formation, and presumably the formation extends south at least as far as the valley of Apatzingán. It reappears from beneath the younger volcanoes to the west of Parícutin in the low country between San Francisco and Los Reyes.

Except on Cerro de Charanda, close to Uruapan, where the beds are tilted to a high angle, the Zumpinito formation lies either horizontally or has low initial dips. No original volcanic forms are preserved; hence the erosional topography carved in the rocks of the Zumpinito formation contrasts boldly with the constructional forms built by the later volcanoes. Nor is it possible to locate any of the vents from which the lavas and fragmental ejecta of the Zumpinito formation were expelled.

No fossil evidence has yet been found which indicates the age of the Zumpinito formation. Since, however, the formation includes at least one major disconformity and was already deeply dissected before the Tancítaro volcano began to develop, it must cover a long span of Tertiary time, and the topmost beds can hardly be younger than middle Pliocene.

Probably the Zumpinito formation is equivalent to the great mass of predominantly andesitic lavas that makes up the rugged country between Morelia and Zitácuaro, and presumably it is also to be correlated with the early volcanic rocks bordering the valley of Mexico.

To those familiar with the Cascade Range in the United States, the Zumpinito formation will call to mind the Eocene to Miocene volcanic rocks of the western Cascades, just as the younger volcanoes of the Parícutin region will call to mind the Pliocene, Pleistocene, and Recent cones of the high Cascades.

DETAILED DESCRIPTION

In composition the rocks of the Zumpinito formation within the area in question range from olivine-rich basalts to rhyolites. On Cerro de La Cruz and Cerro Colorado, as well as in the mountainous country crossed by the Uruapan-Apatzingán road, lavas predominate. Among the hills limiting the plain of Uruapan on the east and southeast, deeply weathered tuffaceous sediments are more abundant; in the gorge of the Río de Cupatitzio and the low country near Los Reyes, coarse, bouldery mudflow deposits are the principal units. Noteworthy is the marked lateral and vertical variation within the formation.

The oldest beds of the Zumpinito formation are those to be seen in the gorges of the Río de Cupatitzio and Río de Los Conejos near the Zumpinito hydroelectric plant and Cascada de Tzaráracua. These are deposits of volcanic mudflows or lahars. Their thickness approximates 450 feet. Typically they are chaotic, unstratified beds in which angular and subangular blocks up to 10 feet across lie in a pale-gray tuffaceous matrix. Most of the larger fragments are of hornblende andesite; with these are pieces of pyroxene andesite, dacite, and basalt. The fine matrix consists of andesitic crystalvitric tuff. Locally lenses of andesitic tuff and conglomerate separate the sheets of laharic debris, but they are quite subordinate. Except for a few thin layers of air-borne ejecta, all the deposits were laid down either by streams or by torrential volcanic mudflows.

Other laharic deposits accompanied by tuffs and tuffaceous clays crop out near Peribán and Los Reyes. Hereabouts they are partly covered by Recent flows of olivine basalt and by Pleistocene and Recent laharic beds deposited by torrents from the flanks of Cerros de Tancítaro. Indeed, beds of somewhat similar character are being laid down today by floods that wash the newly fallen ash from Parícutin into the canyons to mingle with water-worn boulders of andesite from the Tancítaro cone.

Near the type locality, the coarse laharic detritus grades upward into brownish and reddish tuffaceous clays, the transition zone forming benches along the rim of the Cupatitzio gorge. Close to the road that skirts the foot of Cerro de Jicalán the clays have been extensively quarried for the making of adobe bricks.

A short distance to the south, where the Apatzingán road crosses the Río de Los Conejos, the clays are covered in turn by spheroidally weathered flows of olivine basalt. These continue westward for about 2 miles. Farther west, an upper series of laharic deposits is exposed; then for 6 miles to the summit of the pass, the road crosses massive flows of porphyritic pyroxene andesite.

A similar assemblage of rocks forms the dissected country traversed by the trail leading from Los Conejos through Los Lobos and Las Barrancas. Here, and particularly in the canyons of the Río del Fresno and its tributaries, there is evidence that the Zumpinito formation was already deeply eroded before the first flows of the Tancítaro volcano were erupted. Near Tejamanil, the disconformable contacts lie at about the same elevation as the base of Parícutin, approximately 8 miles to the north.

Attention is directed next to the hills flanking the plain of Uruapan on the east. Where the Río de San Antonio is incised into the plain, the canyon walls reveal coarse laharic beds. Overlying these are varicolored and intensely weathered tuffaceous clays, between 600 and 700 feet in thickness. These form most of Cerro de Las Ventanas and the adjacent Cerro de Los Tecates. On the southernmost peak of Cerro de Las Ventanas, the clays are capped by a thick flow of coarsely porphyritic hornblende andesite; on the northern peaks and the neighboring parts of Cerros de Los Tecates, the capping rocks are flows of olivine-rich basalt.

Farther north, among the hills adjoining the Apatzingán railroad, the tuffaceous clays carry many concretions of opal and chalcedony and occasional geodes lined with drusy quartz. Close to Caltzontzin, in the narrow strip separating the railroad to Apatzingán from the one to Mexico City, the clays are covered by rhyolite tuffs up to 400 feet thick. In their lower part these tuffs are strongly welded, pinkish, streakily banded rocks that simulate lavas; upward they become less compact and finally grade into friable lump pumice. Hence they are regarded as the products of nuées ardentes. Before the overlying beds were laid down, a long period of erosion intervened. Discussion of the evidence is best deferred, however, until the Zumpinito rocks on Cerro de La Cruz and Cerro de Charanda are described.

Cerro de La Cruz, the high peak that rises from the edge of Uruapan, is composed chiefly of flows of pyroxene andesite that are almost horizontal. Hence the conical form of the mountain (fig. 82), though deceptively like that of many younger volcanoes in the region, is solely the result of erosion. Much of the lava on the higher parts of the mountain is thoroughly decomposed. Where the flows are thick and cut by vertical joints, the weathering is spheroidal; where they are marked by closely set, flattish joints, thin plates of fresh andesite are encased in bands of brownish clay up to several feet in thickness. Locally, indeed, alteration has gone so far that the lavas are difficult to distinguish from lapilli tuffs and agglomerates, sporadic kernels of unaltered rock lying in a tufflike matrix of clay. These alterations are ascribed, not to deuteric solutions, but to weathering in a climate warmer and more humid than that which now prevails.

The lower slopes of the mountain consist mainly of rotten tuffs and tuffaceous sediments similar to and probably of the same age as those seen on Cerro de Las Ventanas.

At the southwest foot of the mountain lies the small hill known, on account of the red, loose, crumbling earth of which it is largely composed, as Cerro de Charanda. Its steeper face has been widely stripped for clay used in the local adobe factory. Interbedded with the clay are thin layers of tuff breccia and flows of decomposed olivine basalt that dip to the southwest at angles of approximately 30°. On the summit and eastern slopes of the hill exposures are scarce and only tuffaceous clays are to be seen. It appears, therefore, that Cerro de Charanda is a tilted block and that the gully separating it from Cerro de La Cruz was developed by erosion along a fracture zone.

We may now return to the vicinity of Caltzontzin for evidence of a pronounced disconformity within the Zumpinito formation. Thereabouts the hummocky top of the rhyolite tuffs already described as products of nuées ardentes is patchily covered by well-rounded fluviatile sands and conglomerates largely composed of rhyolitic debris. Resting on these is a thick series of basaltic flows that makes up most of Cerro Colorado. Southeastward from their contact with the rhyolitic sediments, the basal flows of basalt are traceable for about 2 miles down a slope averaging 10° to 15°, so that they rest on successively lower units of the Zumpinito formation. In the opposite direction they lie on reddish-brown tuffaceous clays similar to those that underlie the rhyolitic tuffs and those that form the lower slopes of Cerro de La Cruz. Possibly the andesite flows forming the upper slopes of Cerro de La Cruz once covered the rhyolitic tuffs and were removed by erosion prior to the eruptions of basalt. Alternatively, the andesitic and basaltic flows are approximately coeval. Unfortunately the evidence on which to base a decision is buried by Recent flows that fill the valley between the two mountains. If the first suggestion is correct, the erosion surface cut before the discharge of the basalts had a relief of more than 2,500 feet; and even if the other suggestion is the proper one, the relief was more than 1,000 feet.

The basalts of Cerro Colorado are highly vesicular, thoroughly decomposed flows abnormally rich in iddingsite. They are exposed in magnificent sections along the railroads that wind across the lower slopes (fig. 82). Nothing characterizes them more than their spheroidal weathering, with ovoid kernels of relatively fresh lava lying in a rotted, clayey matrix. On the higher flanks of the mountain these rounded kernels, from the size of peas to 6 feet across, are littered in profusion over the surface. Some of the alteration of the flows may well be the result of deuteric solutions, but, as in the case of the andesitic flows of Cerro de La Cruz and the tuffaceous clays in other parts of the Zumpinito formation, the prime cause is thought to be weathering under the warmer and wetter climate that prevailed at the time of deposition.

INTRUSIVE ROCKS OF UNDETERMINED AGE

At two localities in the Parícutin region, the Zumpinito formation is associated with coarse-grained intrusive rocks. The first of these is at Parícutin volcano itself. During the early stages of growth the new volcano blew out many large fragments of plutonic rock, chiefly quartz monzonite but perhaps also granite and diorite. The number and size of the fragments have since diminished until now those found in the lavas and bombs are extremely rare and small. They are described more fully on pages 258–259. Here it is enough to remark that there is no satisfactory evidence to show whether the fragments were torn from a plutonic basement beneath the Zumpinito formation or from a body intrusive into them. Quartz monzonites and diorites are widespread around Jorullo, and they also occur as inclusions in the lavas and fragmental ejecta of that volcano. Ordóñez (1906) held the view that similar plutonic rocks underlie the vast accumulation of lavas forming the plateaus of Ario de Rosales and Pátzcuaro. As to their age, the evidence is meager. Robles (1942) says that many plutonic rocks in the Neo-Volcanic Zone of Mexico date back to late Eocene or possibly to late Mesozoic time. De la O. Carreño (1943) and others assign them merely to the early Cenozoic. Probably many of them form stocks intrusive into the early Tertiary lavas, like the stocks intruded among coeval flows in the Cascade Range of the United States.

The other locality where intrusive rocks are found is a low ridge, called the Bolita or Cerrito de La Magdalena, that rises from the plains about a mile and a half south of Uruapan. Many shallow clay pits have been dug in the summit of the ridge, but none penetrates the mantle of decomposed ash to the underlying rocks. Only in the quarry at the western end of the ridge are these revealed. Here gabbroid rocks of extremely variable texture are cut by thin veinlets of pegmatite. Except for a few boulderlike kernels of fresh material, the rocks are thoroughly rotted to whitish and reddish-brown clay. Their microscopic features are described on pages 233–234. Here it suffices to note that both the field appearance and microscopic textures are so radically different from those of any of the volcanics in the Zumpinito formation that their intrusive character is hardly to be questioned even though no contacts are to be seen. Whether they form part of a basement of pre-Zumpinito age or, as seems more likely, represent a minor intrusion into the Zumpinito formation remains uncertain.

If the intrusive rocks just described do actually come from a plutonic floor, then that floor must have been deeply dissected prior to deposition of the Zumpinito formation; and even if they merely represent minor stocks intrusive into that formation, they serve to show that a long interval of erosion preceded the growth of Tancítaro and the younger volcanoes of the Parícutin region.

OLDER VOLCANOES OF POST-ZUMPINITO AGE

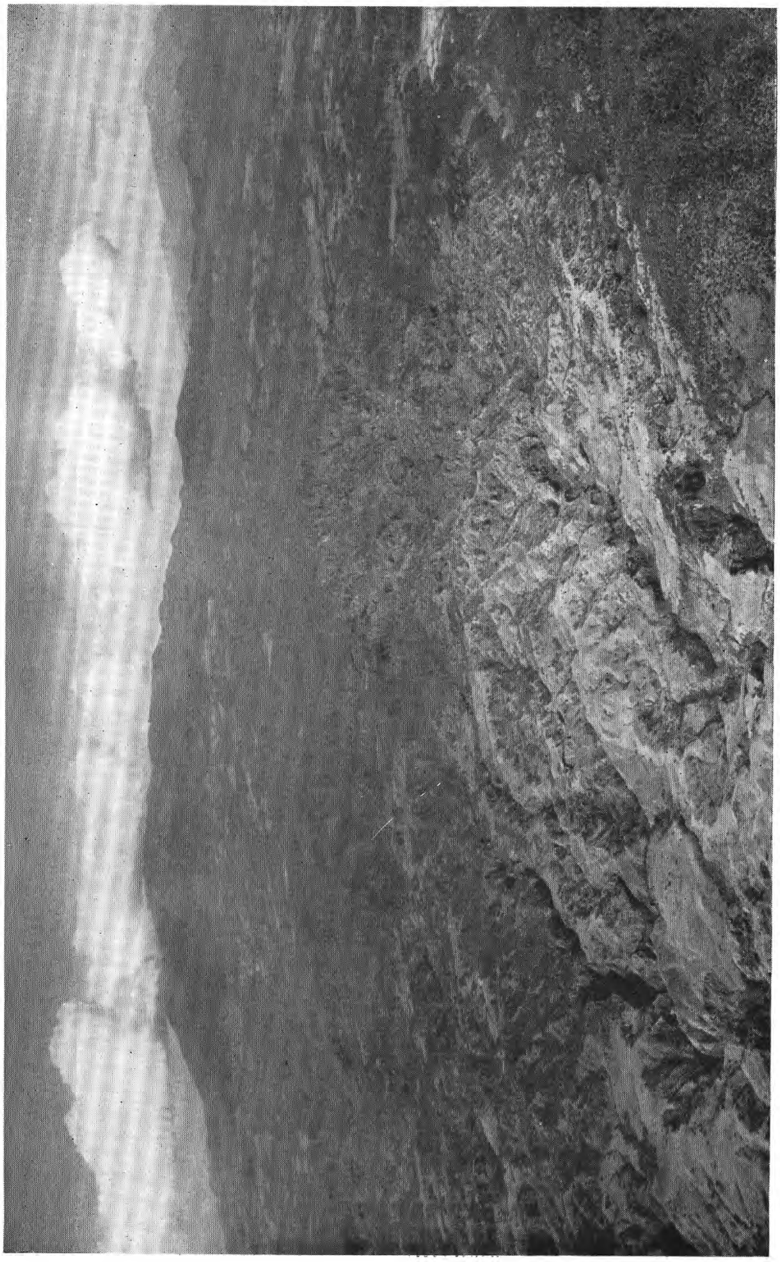
CERROS DE TANCITARO

The oldest volcano of post-Zumpinito age forms the towering mass of Cerros de Tancítaro, the highest peak in the State of Michoacán. Its summit rises to an elevation of almost 13,000 feet, providing an unparalleled view over an immense volcanic field dotted with hundreds of lesser cones.

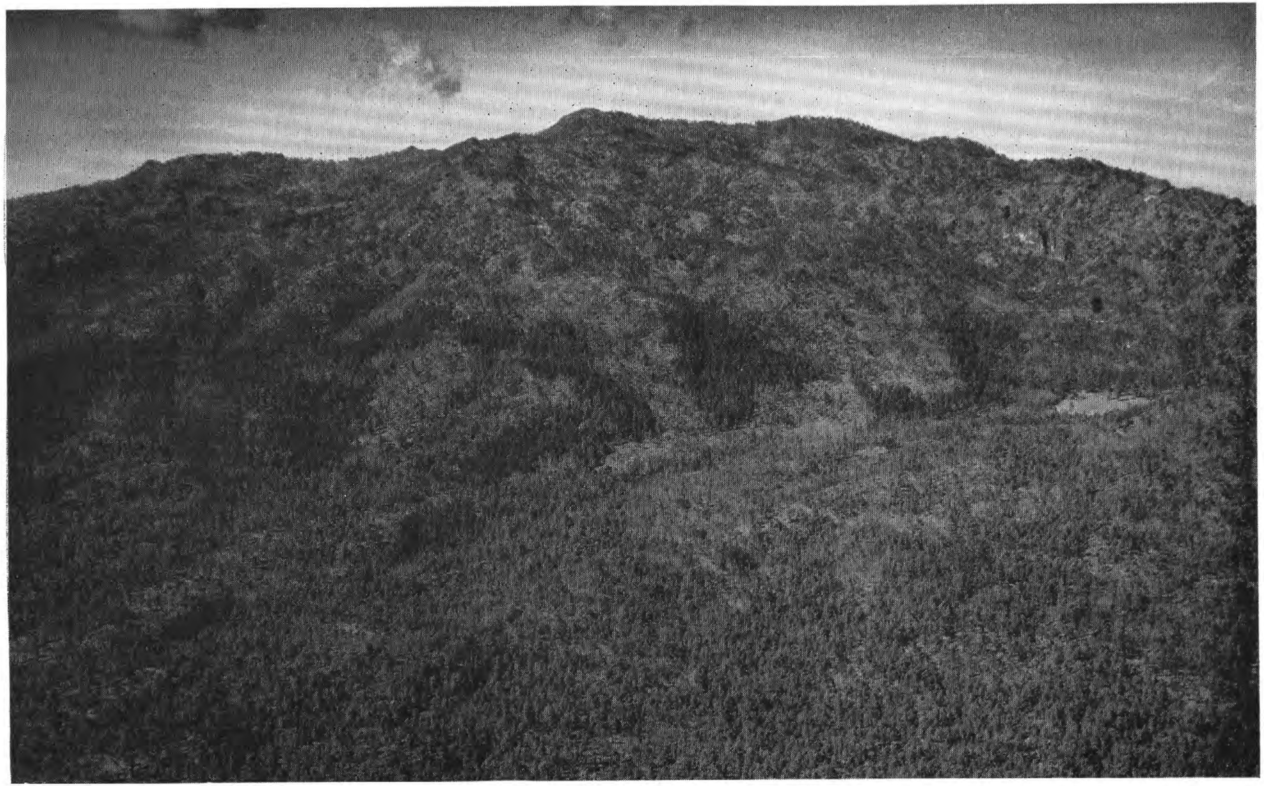
Prior to dissection, the form of the Tancítaro volcano approximated that of a shield with slopes flattening toward the top (fig. 75). The visible diameter of the volcano is about 7 miles; its buried extent may be twice as much, for the lower flanks are covered by the flows and fragmental ejecta of younger, basaltic cones. Where the lavas of the Tancítaro volcano disappear beneath these younger rocks there is a distinct break in slope and the topography changes suddenly, narrow ridges giving place to flat-topped divides of gentler gradient.

Erosion of Tancítaro has advanced to full maturity, so that the original shield has been reduced to radiating, sharp-crested spurs separated by V-shaped canyons, some of which exceed 1,000 feet in depth. On all sides the ridge crests descend in approximate conformity with the dips of the constituent flows. None of the original constructional surfaces remain, but some of the sharp ridges close to the foot of the mountain merge into flat-topped, wedge-shaped interfluves that coincide fairly closely with the initial flanks. Such slightly modified planezes may be seen, for example, among the spurs that adjoin the village of Zirosto.

The attitudes of the flows on the upper part of the mountain indicate that the main vent or vents lay between the present summit and the



A



B

FIGURE 75.—Views of Cerros de Tancítaro. *A*, Looking north to Cerros de Tancítaro across terrain occupied by the eroded Zumpinito formation. To the right of Tancítaro, in shadow, the young volcano of Cerro Prieto. *B*, East-northeast slope of Cerros de Tancítaro, showing the eroded shield form of the volcano. Photographs by the Compañía Mexicana Aerofoto, 1934.

conspicuous peak known as Peña del Horno, about a mile to the north. Probably subsidiary vents served as feeders to parasitic cones close to the summit; if not, it is difficult to account for the numerous peaks that cluster around the highest point. All signs of the main and subsidiary craters have long since disappeared (fig. 76).

The eruptions that built Cerros de Tancítaro were almost all of the quiet, effusive type. Some interbeds of breccia and agglomerate were observed by Ordóñez (1910), but compared with the lavas they are very minor in amount. Dominantly the volcano consists of massive sheets of porphyritic andesite, some of which exceed 200 feet in thickness. Apparently the flows were extremely viscous, and many, in the later stages of advance, moved by shearing rather than by laminar flow, so that highly inclined and vertical joints were developed at steep angles to the fluidal banding. True obsidians were not observed, but most of the flows are rich in interstitial glass. Some show columnar structure; others exhibit reddened, scoriaceous crusts.

A few flows of hornblende-rich andesite are present, but most of the lavas are hypersthene-augite andesites plentifully studded with large phenocrysts of feldspar. According to Ordóñez, they resemble the principal flows of Cofre de Perote, Ajusco, and Ixtaccíhuatl, and they are identical with the andesites forming the coeval volcanoes of Cerros de San Marcos. They also call to mind the andesites that compose such volcanoes of the Cascade Range as Mounts Shasta, Rainier, and Hood.

Reference has already been made to the fact that previous workers considered the Tancítaro volcano to be of Pliocene or Eocene age. The latter estimate may be dismissed from consideration with the remark that no volcano of such antiquity would preserve any semblance of its original shape. However, in attempting to assign a more precise age to the volcano, there is little evidence upon which to rely. The volcano grew upon the deeply eroded surface of the Zumpinito formation, but the age of those bedrocks is still unknown. In using the degree of dissection as a criterion, it must be borne in mind that erosion has been tremendously accelerated in this region as a consequence of the explosive activity of the younger volcanoes. Every explosion of these younger cones blanketed the flanks of Tancítaro with fine ash, and during every rainy season the ejecta must have been swept into the canyons, converting the streams into muddy torrents of exceptional abrasive power. This acceleration of erosion is vividly seen today as the new cover of ash from Parícutin is stripped from the steep hillsides during the wet summers and devastating mudflows rush down the canyons to spread their bouldery loads in huge fans far beyond the base of Cerros de Tancítaro. Coarse deposits of older lahars have built great fans around the foot of the mountain. All are

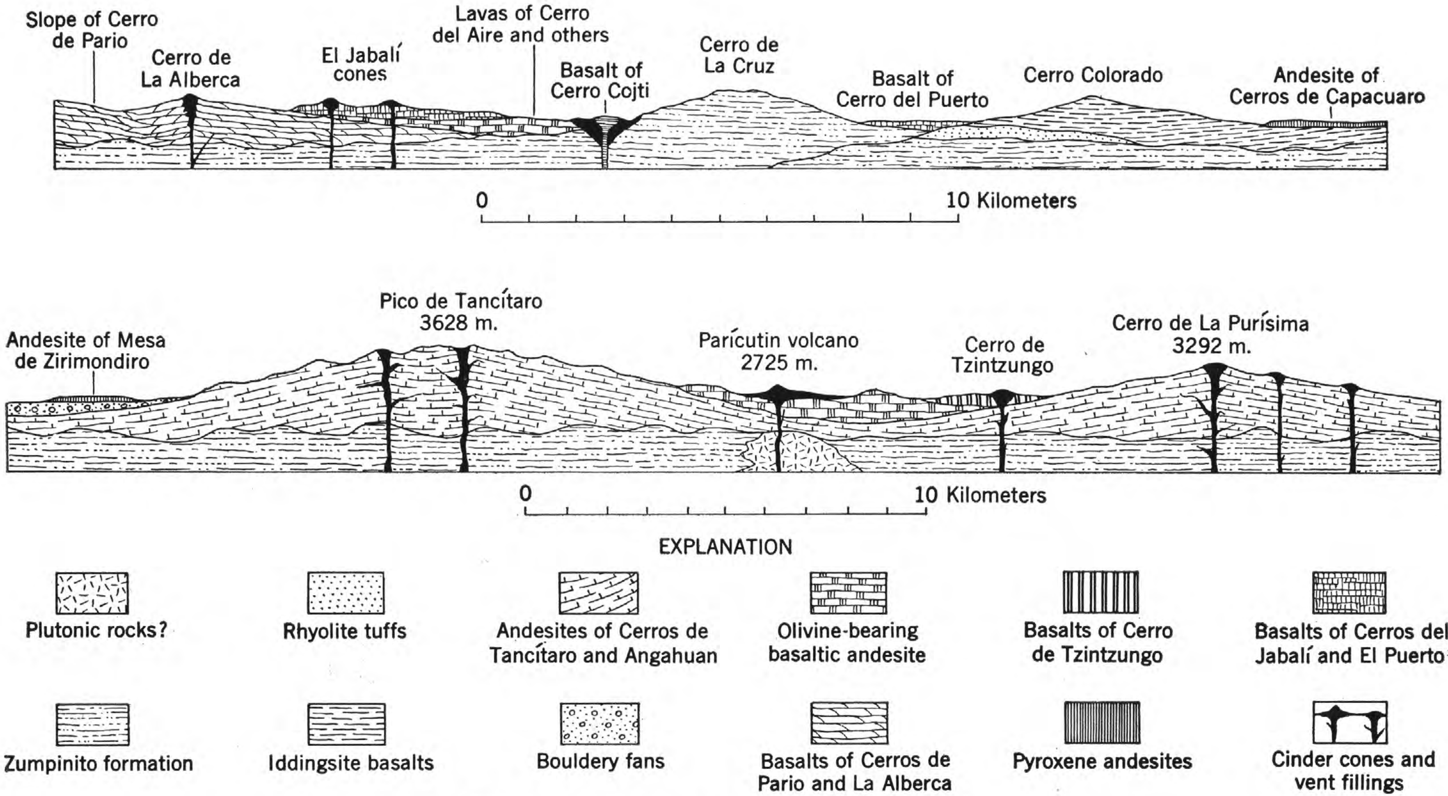


FIGURE 76.—Generalized geologic sections across the Parícutin region.

mantled by deeply weathered basaltic ash, locally as much as 50 feet in thickness, and in places beds of ash and flows of olivine basalt are interstratified with the bouldery debris. From this it follows that unusually rapid erosion of Tancítaro persisted throughout the growth of the encircling cones of basalt. Bearing in mind also that some of the present ridge tops almost coincide with the original slopes of the volcano and that dissection, although mature, has not proceeded far enough to expose the central feeding pipes, it can hardly be doubted that the last eruptions of Tancítaro took place either in late Pliocene or Pleistocene time.

Finally, it should be noted that no signs of glaciation have been detected on Tancítaro despite its great height. Their absence is significant in connection with the view advocated by some Mexican geologists that glaciers formerly spread far down the flanks of the valley of Mexico to elevations several thousands of feet lower than the summit peaks of Cerros de Tancítaro.

CERROS DE SAN MARCOS AND CERRO DEL AGUILA

The paved highway connecting Capacuaro, Paracho, Aranza, and Cherán skirts the base of a long ridge trending northeast (pl. 8). This ridge is formed by a line of coalescing volcanoes, the oldest of which are andesitic cones that rise as conspicuous peaks—those of Cerros de San Marcos at the northern end of the ridge and Cerro del Aguila at the opposite end. In the intervening saddle lies Cerros de Paracho, composed of younger flows of basalt and basaltic andesite. Only narrow ravines cut the broad, gently rounded slopes of Cerros de Paracho; on the other hand, the older andesitic cones are scored by profound, V-shaped canyons between narrow-crested ridges. Judging by these criteria—and no other are available—the San Marcos volcanoes are slightly older than Cerro del Aguila and of approximately the same age as Tancítaro.

Circumstances prevented a close study of the San Marcos peaks, but reconnaissance of the lower slopes, coupled with examination of aerial photographs, indicates that they represent two overlapping volcanoes on a northwest-southeast line. The northwestern one, overlooking the village of Cherán, is capped by a monolith of lava approximately 300 feet high. A distant view is enough to suggest that this marks the filling of the central conduit. On the cliffed walls of the canyons below the summit pinnacle, several thick flows are exposed. Specimens collected by Krauskopf from some of the canyons and by the writer from the fans at the mouths of others show that the volcano is composed of pyroxene andesites identical with those of Tancítaro. If pyroclastic interbeds are present, they must be in quite subordinate amount. Similar andesites make up the southeastern volcano. This seems to be younger than its neighbor, for erosion has still to reveal the central conduit. In place of a summit pinnacle, the top is marked by a shallow basin almost surrounded by jagged peaks of lava.

Cerro del Aguila rises to a height of more than 10,000 feet. No landmark in the Parícutin region is more distinctive (fig. 77). Most of the younger volcanoes are surmounted by a symmetrical cinder cone, but Cerro del Aguila is capped by a huge, towerlike mass with precipitous walls and flattish top. Below the summit tower the flanks of the principal cone slope at angles of about 13° and consist of dark-gray and black, vesicular pyroxene andesite flows rich in porphyritic feldspar. Owing to the heavy blanket of ash blown from adjacent cones, exposures are scarce, and none reveals the presence of fragmental layers between the flows of andesite.

A discontinuous moat separates the principal lava cone from the summit tower. On its northern and western sides, the tower rises almost vertically to heights of 300 to 400 feet; on other sides the walls are lower. The constituent materials are yellowish tuff breccias and lapilli tuffs. Few of the larger fragments exceed a yard in diameter, and most measure less than a foot across. The majority are composed of dense, glassy andesite; these were erupted in a solid state. With them are scoriaceous lumps that were partly molten when discharged. Rounded, spindle- and almond-shaped bombs are lacking. The inference is that most of the culminating explosions of Cerro del Aguila were of the low-temperature Vulcanian or Ultra-Vulcanian type.

Throughout most of the summit tower the fragmental ejecta show no stratification. Where bedding can be seen, it dips outward more or less radially. On the southwest face the dips increase locally to as much as 50°, an inclination far steeper than the normal angle of repose for such ejecta. Presumably a concealed intrusion within the tower is responsible for this upward deflection. Similar upturning of tuff breccias by plugs of lava has been observed on many summit cones of the volcanoes of the Cascade Range in Oregon (Williams, 1933). At least in its upper part the tower of Cerro del Aguila represents a deeply denuded cone rather than the filling of the feeding conduit. If so, the fragmental cone was built within a deep, steep-sided crater about two-thirds of a mile wide, and it continued to grow until it overlapped the crater rim and spread onto the gentle outer slopes of the principal lava cone beyond.

Low on the western flank of Cerro del Aguila there are three cinder cones, one of which, known as Cerro de Capatacutiro, erupted a flood of pahoehoe basalt in recent times (pp. 252–253). These cones are so much younger than Cerro del Aguila itself that they cannot be regarded as parasitic structures; on the contrary, they developed long after Cerro del Aguila had become extinct, and they were probably fed from independent fissures.

FIGURE 77.—Cerro del Aguila from the south side. The main cone of andesitic lavas is capped by an eroded cone of tuff breccias. Low on the left (west) slope of the mountain rises the small basaltic cone of Cerro de Capatacutiro, from which a recent flow of pahoehoe lava was erupted. Beyond, in the flats, are two of the basaltic cones near the village of Paracho. Photograph by the Compañía Mexicana Aerofoto, 1934.

CERROS DE ANGAHUAN

After the formation of the andesitic cones of Tancítaro and San Marcos, and approximately at the same time that Cerro del Aguila was active, two other andesitic volcanoes developed near the village of Angahuan. These form the conspicuous Cerros de Angahuan (fig. 78), culminating in Cerro de La Purísima at an elevation of 10,864 feet.

Like Cerros de San Marcos, Cerros de Angahuan consists of two coalescing cones, the craters of which have been obliterated and the flanks of which are deeply trenched by radial ravines. Their lower slopes are buried by wide alluvial fans. Southward the lavas of these volcanoes pass under the basaltic flows of Nureto, Tzintzungo, and Cutzato; westward and northward they pass under basaltic flows and ashes erupted from cones near Corupo and San Felipe. Eastward they are partly overlain by olivine-bearing basaltic andesites discharged by Apupan, Matáncero, and adjacent cones and partly by still younger flows of olivine-bearing andesite that poured from the Surúndaro volcano.

Judging by the degree of dissection and the thickness of the ash cover, the two Angahuan volcanoes are of approximately the same age. The top of the northern one is an irregular, hummocky plateau that drops off precipitously in cliffs of massive andesite. The top of the other is marked by two sharp pinnacles that may be the fillings of the feeding pipes.

Except in texture the lavas composing both volcanoes show little variation. Most of them are black, olivine-free pyroxene andesites liberally sprinkled with porphyritic feldspar in a matrix of glass. Other flows are virtually devoid of phenocrysts and approximate obsidians in character. On the higher slopes of the northern cone, many flows are so markedly vesicular as to appear scoriaceous.

The activity of both volcanoes came to a close long before such cinder cones as Apupan, Matáncero, Cumbundicato, and Terutsjuata began to erupt on their flanks and around their feet. Consequently these minor cones are not regarded as products of lateral or eccentric eruptions but as independent forms built over separate feeding chambers.

CERROS DE LOS HORNOS

A large, multiple volcano rises about 1,500 feet above the village of San Lorenzo. It measures 4 miles across the base, and it was built on a floor sloping downward steeply to the south. Its last eruptions followed those of the Angahuan volcanoes and Cerro del Aguila.

A heavy cover of ash and vegetation masks all but a few poor exposures of the rocks forming these hills, but the topographic forms

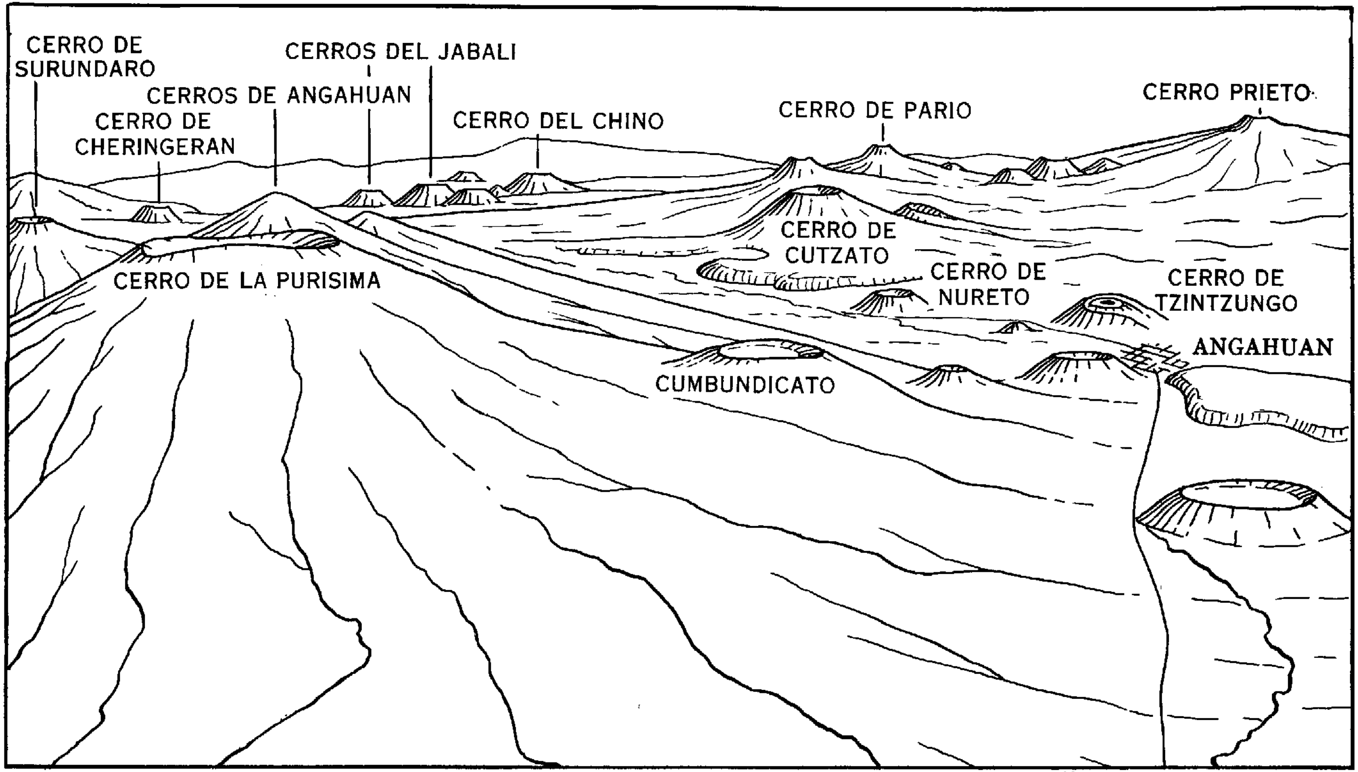


FIGURE 78.—Cerros de Angahuan from the northwest, showing the relation of these large eroded andesitic cones to the younger volcanoes in the vicinity. Photograph above (p. 186) by the Compañía Mexicana Aerofoto, 1934.

denote a group of overlapping cones and the available outcrops indicate that the cones consist partly of basalt and partly of basaltic andesite. Specimens found near the foot of the hills on the east, north, and southwest sides are dense, glass-rich hypersthene andesites like the principal lavas of the Angahuan volcanoes. Other specimens, chiefly from the southeast slopes, are olivine-bearing basalts or basaltic andesites. Unfortunately their sequence could not be determined.

The summit peaks, from which the hills take their name, are denuded, craterless cones of basaltic scoria. These had become extinct before three youthful cones were formed on the eastern flank of the Cerros de Los Hornos and a small volcano made up of olivine basalt developed close to the village of Capacuaro.

YOUNGER VOLCANOES

GENERAL STATEMENT

After the growth of the large andesitic volcanoes of Tancítaro, San Marcos, Angahuan, and Cerro del Aguila and the mixed eruptions of Cerros de Los Hornos, the centers of activity in the Parícutin region became more numerous and widespread, and the dominant lavas changed to olivine basalts and olivine-bearing basaltic andesites. Eruptions of pyroxene andesite did not come to an end; on the contrary, some of the most copious flows of andesite were discharged within the last few thousand years.

These younger volcanoes, whose symmetrical forms typify the Tarascan landscape, are so little modified by erosion that all can be assigned without hesitation to recent time. While they were active, other eruptions continued throughout the length of the Neo-Volcanic Zone of Mexico from San Andrés Tuxtla, bordering the Gulf of Mexico, to the vicinity of Tepic, close to the Pacific coast. It was then that most of the volcanoes of the Pátzcuaro region and the basaltic cones around the valley of Mexico and Apatzingán were formed, and it was then that the highest volcanoes of Mexico—Popocatépetl, Orizaba, Nevado de Colima, and Nevado de Toluca—which began to grow during Pleistocene or late Pliocene time, passed through maturity to their present stage of decline.

STRUCTURAL TRENDS

Most of the Neo-Volcanic Zone from Colima to Orizaba trends approximately east, but at the extremities the trend changes. Thus the volcanoes of the Tuxtla group and those between Guadalajara and Tepic are alined in a northwest to north-northwest direction. Hobbs (1944) has suggested the possibility that the recent volcanism of Mexico and Central America is related to a rising anticline parallel to the foredeeps off the Pacific coast. Certainly in Central America the active cones are alined parallel to the adjacent deeps, but in Mexico the trends diverge widely. During the last few centuries eruptions have occurred in Mexico at the following places: Tres Virgenes (Baja California), Ceboruco, Colima, Parícutin, Jabalí, Jorullo, Popocatépetl, and San Martín Tuxtla. In other words, the latest eruptions have taken place at points scattered along the full length of the Neo-Volcanic Zone. Their distribution bears no apparent relation to the structural features referred to by Hobbs (1944).

Within the main east-west zone in Mexico, the individual volcanoes show little alinement. Locally they are disposed at right angles to the belt itself. Thus Cofre de Perote lies north of Orizaba, and Ixtaccíhuatl lies north of Popocatépetl. Several volcanoes in Java, though grouped in a broad east-west belt, are likewise alined perpendicular to the dominant trend.

Within the Parícutin region, most of the cones appear to be scattered haphazardly. Locally, however, a northeast alinement may be detected. Thus the old andesitic cones of Cerros de San Marcos and Cerro del Aguila, together with the younger cones of Cerros de Paracho and Cerros de Los Hornos, exhibit this alinement. More striking is the parallel series of youthful cinder cones including Pelón, Cumbuén, and Paracho Viejo (pl. 8). Indeed, if the line joining these three cones is prolonged, it passes through Parícutin volcano, through its parasite, Sapichu, and through the fissure-and-tremor zone on the opposite side of the new volcano. Other examples of the same alinement include Cutzato and its parasite, Pantzingo. The principal vent of Cerro Cojti lies northeast of the minor cone on its crater rim; the vents of Cerro de Curitzerán, Cerro del Anillo, and Cerro de Sicuín are on a parallel line; the central vent of Cerro de Pario lies northeast of the main vent of Cerro Prieto, just as the triple cone of Cerro del Aire lies northeast of the summit vent of Cerro de La Alberca. Moreover, it may not be fortuitous that the Jabalí and Capacuaro volcanoes, which are among the youngest in the region, are also on a northeast-southwest line.

However, the general rule deserves emphasis: lack of regular orientation characterizes most of the volcanoes of the region. Cinder cones cap many of the larger lava volcanoes, but they are most numerous in the depressions separating the major structures. A few cinder cones are disposed more or less radially on the flanks of the principal volcanoes; these may be considered as parasites. Most of them, however, are either products of eccentric eruptions of the main volcanoes or, more likely, were fed through independent fissures.

In the part of Michoacán lying to the north and east of Parícutin, Blásquez (1946b) has observed that the principal mountain ranges, basins, and hot springs follow a rectilinear pattern. One set of faults trends between N. 10° W. and N. 30° W.; the second trends at right angles to the other. The former accounts for the alinement of the Sierras de Venustiano Carranza, Cerro Azul, and Cerro Purépero not far to the north and northwest of Parícutin; the latter accounts for the orientation of the Sierras de Patamban, Ozumatlán, and Santa Clara, which lie to the north and east of Parícutin. The main depressions between these and parallel ranges trend approximately east. Especially striking are those that hold the great lakes of Cuitzeo and Chapala; less conspicuous and more irregular are the basins of Zamora, Zacapu, and Pátzcuaro. Presumably all are graben. Most of the faulting responsible for them probably took place during the first stages of volcanism in the Parícutin region. Yet within that region there is no hint of any alinement of cones parallel to the dominant trends of northern Michoacán and Jalisco. As noted already, the only distinct alinement of cones near Parícutin is one that trends northeast, approximately bisecting the major structural trends just enumerated.

Not a single fault scarp is to be seen in the Parícutin region. If any are present, they must be buried by accumulations of younger lava.

Too little is known of the geology of Michoacán, particularly of the prevolcanic history, to warrant further discussion of the influence of structure on the distribution of cones. The general disorder of the younger volcanoes of Michoacán bespeaks an absence of large, thoroughgoing fractures; it suggests discontinuous, short gashes such as might be produced by horizontal movements of small extent. Graton (1945a) has likewise cast doubt on the conception of master east-west fractures in the Neo-Volcanic Zone of Mexico, pointing to the absence of chains of minor cones linking the great volcanoes. Also, he has properly doubted that the smaller, short-lived volcanoes are fed from shallower depths than the longer-lived and larger cones. Their extremely wide distribution and lack of any doming of the adjacent rocks make it seem unlikely that the smaller volcanoes are connected with near-surface laccolithic reservoirs. Moreover, the present study shows that in the Parícutin region there is as much petrographic variation among the lavas of adjacent, short-lived volcanoes as there is among the lavas erupted by most of the long-lived, major volcanoes of Mexico. Possibly more seismic data will throw light on the depths from which the feeding magmas rise.

In the pages that follow, most of the younger volcanoes of the Parícutin region are described in the order of their formation, beginning with the oldest. It should be stressed, however, that the precise succession is often unknown, for the only criteria in many instances are the degree of erosion and the thickness and amount of weathering of the ash cover, all of which are rather unsatisfactory. Besides, the difference in age between many of the cones is at most a few hundreds or a few thousands of years, and probably some cones were active simultaneously. None dates back as far as the Pleistocene epoch.

Close to Parícutin itself the heavy cover of new ash has almost completely obscured the record; for that reason, and because of their proximity to the new volcano, the neighboring cones are discussed under a separate caption.

DESCRIPTION OF INDIVIDUAL VOLCANOES

CERROS DE PARACHO

Reference has already been made (p. 182) to the broad ridge forming the saddle between the andesitic cones of Cerros de San Marcos and Cerro del Aguila. These volcanoes were extinct long before the intervening depression began to be filled by lavas discharged from vents on a northeast-southwest line, the positions of which are now marked by four summit cinder cones. Two smaller and younger cones on the northwest flank of Cerro del Aguila contributed to the filling of the depression, and from one of them a fairly recent flow descended to the Mexico City highway.

The lavas of the four Paracho volcanoes, although heavily mantled by ejecta blown from Paracho Viejo, Pelón, and Cumbuén, are only slightly modified by erosion. Unfortunately only the lower slopes of the Paracho ridge were examined. Study of lavas in place and of debris brought down by streams from the higher slopes suggests that most of the flows on the northern side are either olivine basalts or basaltic andesites, whereas those on the opposite side are olivine-poor or olivine-free pyroxene andesites like those of the Angahuan and Capacuaro volcanoes. Nothing is known of their sequence.

MESA DE ZIRIMONDIRO AND MESA DE HUANARUCUA

At two localities, thick sheets of andesitic lava were extruded without attendant explosions of fragmental ejecta. One of these andesitic flows lies immediately north of the village of Tancítaro, forming the Mesa de Zirimóndiro, approximately 2 miles long and up to a mile in width. Its hummocky, cultivated top is thickly covered with yellowish basaltic ash blown from nearby cinder cones; its steep sides rise 200 to 250 feet above the surrounding alluvial flats. Except in gullies cutting the flanks, natural outcrops of lava are scarce; fortunately a large quarry on the outskirts of Tancítaro village provides excellent exposures. Where fresh, the andesite is pale gray and lightly stippled with large crystals of oxyhornblende and augite; where it has been affected by oxidizing vapors, the color changes to

864334—50——3

pink, the oxyhornblende is almost wholly altered to iron ores, and the dense groundmass is charged with minute flakes of hematite. The entire mesa appears to be the result of a single flow of unusual viscosity; indeed, the final effusion, being unable to spread laterally, piled over the vent to form a domical mound near the northern end of the mesa.

The other mesa is that of Huanárucua (figs. 79, 80), extending from near the village of Angahuan to the foot of the Curitzerán volcano. The road linking Angahuan with San Juan Parangaricutiro and Corupo skirts its edges. Toward the south the mesa falls off abruptly in cliffs and talus slopes 250 to 400 feet in height; toward the north it merges indefinitely into the basaltic flats of Llano de Paquichu.

Huanárucua covers an area measuring 1⅔ by 1¼ miles. The source of the flow lies close to the southeast edge, where a low, elongate mound marks the accumulation of the last-erupted material. The lava closely resembles that of Zirimóndiro. It is likewise devoid of porphyritic feldspar, and its dense microvesicular matrix also varies in color from gray to pink according to the degree of oxidation by fumarolic vapors. The only phenocrysts are a few prisms of augite and brownish-black oxyhornblende.

The gently undulating top of the mesa is blanketed with deeply weathered basaltic ash more than 10 feet thick, some of which was blown from the adjacent cone of Terutsjuata. Judging by the nature and thickness of this ash, the Huanárucua andesite is older than the flows erupted by the cones of Cutzato and Tzintzungo.

CERRO DE JICALAN AND THE TZARARACUA FLOW

The eroded cone adjoining the village of Jicalán is among the largest of its kind. Across the base it measures 1 mile, and it rises 800 feet above a pedestal of the Zumpinito formation clays. The sides are cut by deep barrancas, one of which leads into a breached crater. The cone consists of well-bedded basaltic tuffs and lapilli tuffs carrying sporadic bombs and blocks of basalt up to 6 feet across. Few of the larger lumps show rounding caused by rotation in flight; like the ejecta of Parícutin, most of them are irregular in outline, and their texture varies from dense and glassy to scoriaceous.

From the foot of Cerro de Jicalán an undulating surface slopes gently to the confluence of the Río de Cupatitzio and Río de Los Conejos. Most of this surface is thickly covered with basaltic ash, but locally there are exposures of the underlying vesicular lava. On the precipitous east wall of Los Conejos gorge and the west wall of the Río de Cupatitzio, the same lava is revealed in high cliffs, and it may be traced continuously down the gorges to Cascada de Tzaráracua. Indeed, the falls themselves tumble over the lava, and ribbons of water spout from joints within it. Here the flow occupies a steep-sided valley cut in the coarse tuff breccias of the Zumpinito formation, the diverging columns in the lower part lying normal to the old valley walls. At this point the central part of the flow approximates 180 feet in thickness. The basal part shows closely spaced columns; upward the columns become coarser and cruder, until in the uppermost part of the flow the jointing becomes slabby and platy and almost horizontal. Examination of thin sections under the microscope indicates that this slabby and platy jointing resulted from shearing during the final stages of advance (see pp. 245–246).

The Tzaráracua flow is a basaltic andesite liberally studded with porphyritic olivine. Since the original snout lay not more than 200 or 250 yards downstream from the falls and headward erosion has been facilitated both by the strong jointing of the lava and by the nature of the surrounding tuff breccias, the flow is probably only a few thousand years old. Presumably it issued from fissures at the foot of Cerro de Jicalán.

CERRO DE PARIO AND CERRO DE LA ALBERCA

The summit cinder cone of Cerro de Pario, which rises to an elevation of about 9,000 feet, surmounts the highest of a group of overlapping cones composed of glass-rich, olivine-bearing basalts and basaltic andesites. The cinder cone is well preserved and contains a circular crater approximately 150 feet deep. Crags of scoriaceous lava are exposed below its western rim, but outcrops of the flows that make up the main lava cone are extremely scarce. Five other cinder cones rise from the flanks of the Pario volcano; some of these cap independent lava cones, and from others long flows spread southeastward to Los Conejos. Eight other cinder cones are scattered along the south and west base of the Pario volcano. The order of their formation was not ascertained, but probably all were active at about the same time as the Pario volcano. Immediately south of Los Conejos extrusions of basaltic andesite occurred without accompanying explosions of ash, forming a mesa measuring a mile or so across.

The breached and denuded cone of Cerro de La Alberca, to the east of the Cerro de Pario cluster, caps another large lava cone formed of olivine-bearing basalts and basaltic andesites. Flows from this source spread northward across the old road linking Uruapan with San Juan Parangaricutiro, where they are overlain by tongues of lava related to the cone cluster near San Lorenzo. Southeastward the Alberca flows pass under recent lavas discharged by the Jabalí cones. How far they moved in this direction is uncertain, but possibly they extended as far as the feeding springs of the Río de Cupatitzio.

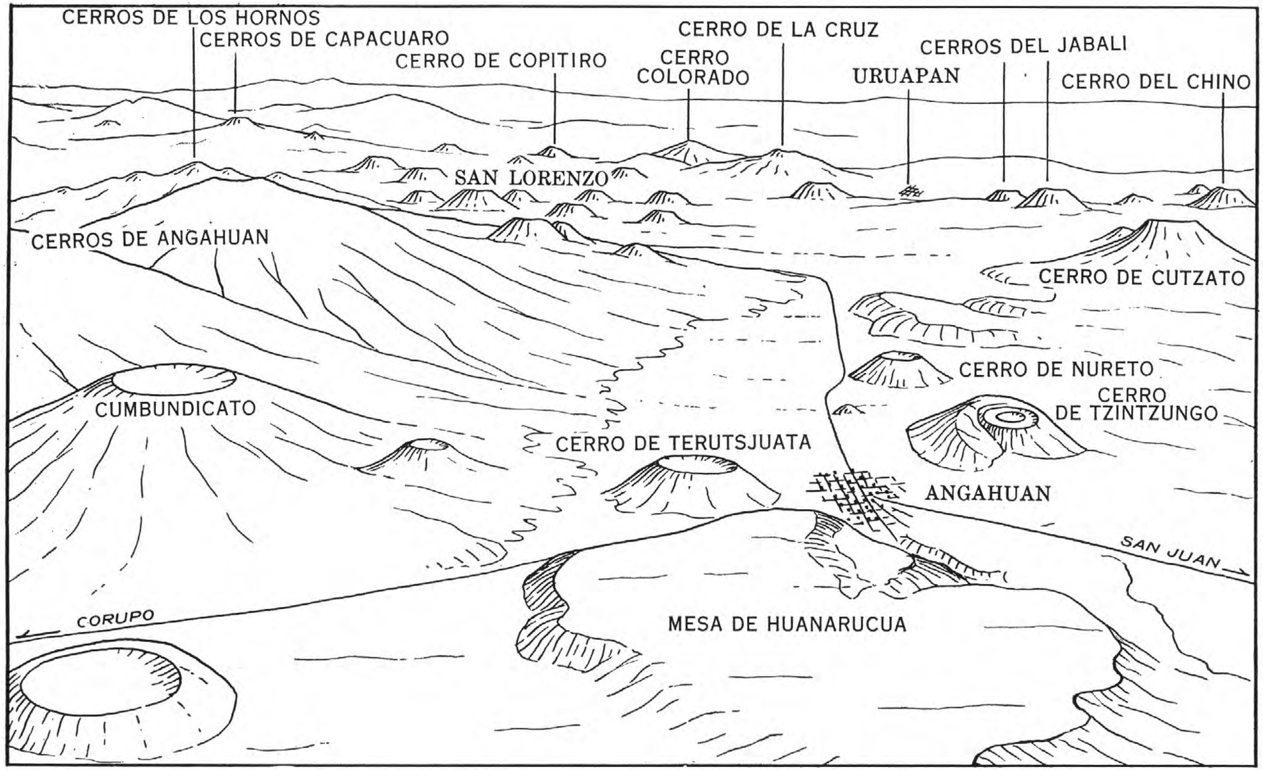


FIGURE 79.—Volcanoes near Angahuan, looking southeast. In the foreground, on the right, the andesitic flow of Mesa de Huanárucua. Older andesitic cones of olivine basalt and basaltic andesite. In the distance the Zumpinito formation forms Cerro Colorado and Cerro de La Cruz. Photograph above (p. 194) by the Compañía Mexicana Aerofoto, 1934.

CERRO DEL AIRE, CERRO DE COPITIRO, AND CERRO DEL PUERTO

Close to the junction of the Mexico City highway and the branch road leading to San Lorenzo is an unusually large group of coalescing cones having a basal diameter of more than a mile and a height of 600 feet. On the summit are three contiguous funnel-shaped craters that range in depth from 20 to 250 feet. These coalescing cones, known as Cerro del Aire, consist of well-stratified cindery lapilli and ash with sporadic bombs. No exotic lithic fragments appear to be present. A short distance to the east is another large cone composed of similar materials, and near its southern base is a mound of lava, approximately 150 feet high, which appears to represent the last viscous extrusion from a separate vent.

The flows from these cones and the adjacent lava mound were unable to move northward on account of the opposing slopes of Cerro del Aguila and Cerros de Los Hornos. How far they spread to the east cannot be ascertained; in that direction they are buried by younger andesites from the Capacuaro volcano. To the south, however, they traveled long distances, reaching at least as far as Cheringerán and possibly as far as Uruapan. The long grade followed by the main highway ascends across their surface, permitting views of the steep fronts of successive tongues. All are scoriaceous and blocky basaltic andesites plentifully charged with phenocrysts of olivine, augite, and feldspar. The yellowish basaltic ash which covers them does not increase in thickness toward the parent cones; on the contrary, its distribution indicates an origin among the younger cinder cones of the vicinity. Hence the explosive activity of Cerro del Aire had either ended or diminished greatly before the main effusions of lava took place. Such has also been the history of Parícutin and of many other volcanoes in the region.

Far down the southern flank of the Cerro del Aire lava pile is the younger cinder cone of Cópitiro, from which a stumpy tongue of coarse-grained, intergranular olivine-augite basalt was erupted. Farther south, in the valley separating Cerro de La Cruz from Cerro Colorado, there are still younger flows of olivine basalt that spread beyond Caltzontzin onto the plain of Uruapan. These issued from the twin cones of Cerro del Puerto and a third cone to the east.

CERRO DE CURITZERAN, CERRO DEL ANILLO, AND CERRO DE SICUIN

The villages of San Juan Parangaricutiro and Zacán are separated by a group of wooded hills crowned by two coalescing cones known as Cerro de Curitzerán, the topmost point of which stands at an elevation of 8,362 feet. These summit cones are only slightly modified by erosion and have well-preserved craters that lie on a line trending west-southwest. Nearby are two smaller cones: Cerro del Anillo, at an elevation of 7,755 feet, and Cerro de Sicuín, at 7,500 feet. Cerro del Anillo is breached on its southwest side. Taken together, the four cones are alined approximately parallel to the main fissure zone at Parícutin.

The visible parts of the two Curitzerán cones are about 500 feet high, but probably these are simply the exposed tops of much larger structures that are mainly buried by encircling lavas, for the flows from these vents form a broad pedestal up to 400 feet in thickness. The longest flows spread to the southwest, descending to the gorge of the Río de Itzícuaro. They are dark, vesicular and scoriaceous, glass-rich, olivine-bearing basaltic andesites that contrast with the pale-gray holocrystalline olivine basalts on the south side of the Río de Itzícuaro.

CERRO DE CHERINGERAN, CERRO COJTI, AND CERRO DEL CHINO

These three cones lie close to Uruapan. Cerro de Cheringerán is one of the largest pyroclastic cones of the entire region, rising to a height of 800 feet. In its summit is a nested crater, an inner depression being separated from an outer by a discontinuous bench. The cone consists of clinkery lapilli and ash and a few irregular bombs up to 6 feet across. Well-rounded fragments and accidental ejecta appear to be absent. Lava escaped from a fissure low on the southwest flank to build a low mound over the orifice.

Cerro del Chino is slightly smaller (fig. 84). It has a saucer-shaped crater, and its outer flanks are about as deeply dissected by radial ravines as those of Cheringerán. Short flows spread from the foot of the cone, chiefly toward the south; judging by the extremely heavy cover of ash, they were discharged before the main explosive activity of the cone had begun. According to Marian Storm (1945), "people still alive remember when ashes showered over Uruapan from the Chino Hill," but this seems doubtful. More probably the ashes were discharged by the neighboring younger cones of the Jabalí cluster, as described on page 210. Nevertheless, it is unlikely that either Cerro del Chino or Cerro Cheringerán dates back more than a few thousand years.

Not far from Cheringerán, at the foot of Cerro de La Cruz, lies Cerro Cojti, a cone that differs from all others in the region by reason of the great width of its crater in relation to the low encircling rim of ejecta (fig. 84). In the terminology of German volcanologists, it would be termed a "Ringwall." It is distinguished further by being the only crater into which lava was extruded after the main explosive activity ended. The rim is a narrow ridge rising no more than 100 to 150 feet above the crater floor except on the east, where the ejecta piled against the slopes of Cerro de La Cruz to a height of 500 feet. On the inner side the rim falls steeply; on the outer side the slopes are more gentle. The rim itself consists of weathered basaltic ash with sporadic lapilli and bombs. On the southwest side it is surmounted by a miniature cone.

The main crater of Cerro Cojti is approximately half a mile wide; the circular biscuit-shaped mound of scoriaceous basaltic lava lying on the floor is about half as wide. Resting on the lava is a thick mantle of ash presumably deposited during the eruptions of the miniature parasitic cone.

A narrow flat-bottomed moat formed by inwash of sediment from the slopes of Cerro de La Cruz separates the central lava cake from the crater rim; hence the original crater may have been much deeper than at present. Even so, its width is remarkable. Possibly the explosion focus lay at a shallow depth, for there is no hint that the crater was enlarged by peripheral collapse of the walls.

CONE CLUSTER NEAR SAN LORENZO

Seven closely spaced cinder cones adjoin the village of San Lorenzo. The smallest is about 250 feet high; the largest is three times that height. All are composed of well-bedded, cindery ash and lapilli, excellent exposures of which may be seen in the quarry excavated into the westernmost cone. Fragments more than 3 inches across are exceptional, and none exhibit rounded or ropy forms indicative of fluidity at the time of discharge. All consist of dense, glass-rich olivine basalt or basaltic andesite. In the aforementioned quarry a few lapilli contain xenocrysts of quartz, but no accidental lithic ejecta were observed.

On all but one of the seven cones, the craters are breached. Particularly striking is the southernmost cone. This is a doublet breached on the south side by two barrancas that have extended headward to enlarge the moat separating the inner from the outer cone. The adjacent Cerro de Cuatzione also is breached on the south side, a deep gorge leading up to a precipitous wall of lava beneath the crater floor. Probably this breach resulted from collapse of the cone when a flow broke from a fissure low on the flank, just as part of the cone of Parícutin was undermined and carried away in June 1943 when lava burst from vents close to the base.

Gullies cut through the flats between the seven cones reveal deposits of weathered ash more than 50 feet in thickness. Beneath this mantle are sporadic outcrops of vesicular olivine basalt.

Judged by the degree to which they have been eroded, the San Lorenzo cones appear to be of about the same age as Cerro de Cheringerán and Cerro del Chino and younger than Cerro del Aire. The two westernmost cones are obviously younger than the lavas of Cerro de Surúndaro, for they deflected the lavas' advance.

CERRO DE CUTZATO

Approximately 4 miles east of Parícutin lies the high cone of Cutzato (figs. 78, 80). Its summit reaches an elevation of 9,240 feet, or about 900 feet above the surrounding flows, and its basal diameter is not much less than a mile. Hence it must be counted among the largest cinder cones of the Parícutin region. Indeed, it may well be that, as in the case of Parícutin volcano itself, much of the lower part of the cone is buried by the encircling lavas.

On the summit is a bowl-shaped crater with walls up to 300 feet in height. The flanks of the cone are deeply scarred by ravines, the size of which has greatly increased since the birth of Parícutin in February 1943. Segerstrom (1950) calculated that, if the present rate of erosion had obtained since Cutzato was built, the cone might not be much more than a century old; but clearly, as he adds, erosion has been much accelerated by accumulation and downwash of ash from Parícutin. Nevertheless, his estimate gives reason to suppose that the final eruptions of Cutzato may have taken place within the present or preceding millennium.

At the southwest base is a parasitic cone, Pantzingo, which is breached on the same side. The fissure connecting the parent and parasitic cones is thus parallel to that linking Parícutin with its parasite, Sapichu. Within the breach of Pantzingo, as within the breaches of Cerro de Terutsjuata, Cerro del Pueblo Viejo, and Cerro de Zacán, is to be found one of the large springs of the region.

Before the explosive activity of Cutzato and Pantzingo came to an end, flows of exceptional thickness and viscosity were discharged, chiefly to the northwest and east. The margins of these flows are steep and in some places almost precipitous, ranging in height from 200 to 300 feet. No flows of this magnitude have yet been erupted by Parícutin. They consist for the most part of gray and pink, microvesicular basaltic andesite devoid of porphyritic feldspar but liberally stippled with large crystals of olivine.

The tops of the Cutzato flows are thickly covered with ash, but the margins do not appear to have been modified much by erosion. Although the lavas are older than those of Cerro de Tzintzungo, they are much younger than those of the Pario volcano.

CERRO DE TZINTZUNGO AND CERRO DE NURETO

The large double cone of Tzintzungo rises from the outskirts of the village of Angahuan to an elevation of approximately 8,350 feet, or about 650 feet above the lavas at the base. A small inner cone partly fills the breach on the western side of the main cone (figs. 78, 79).

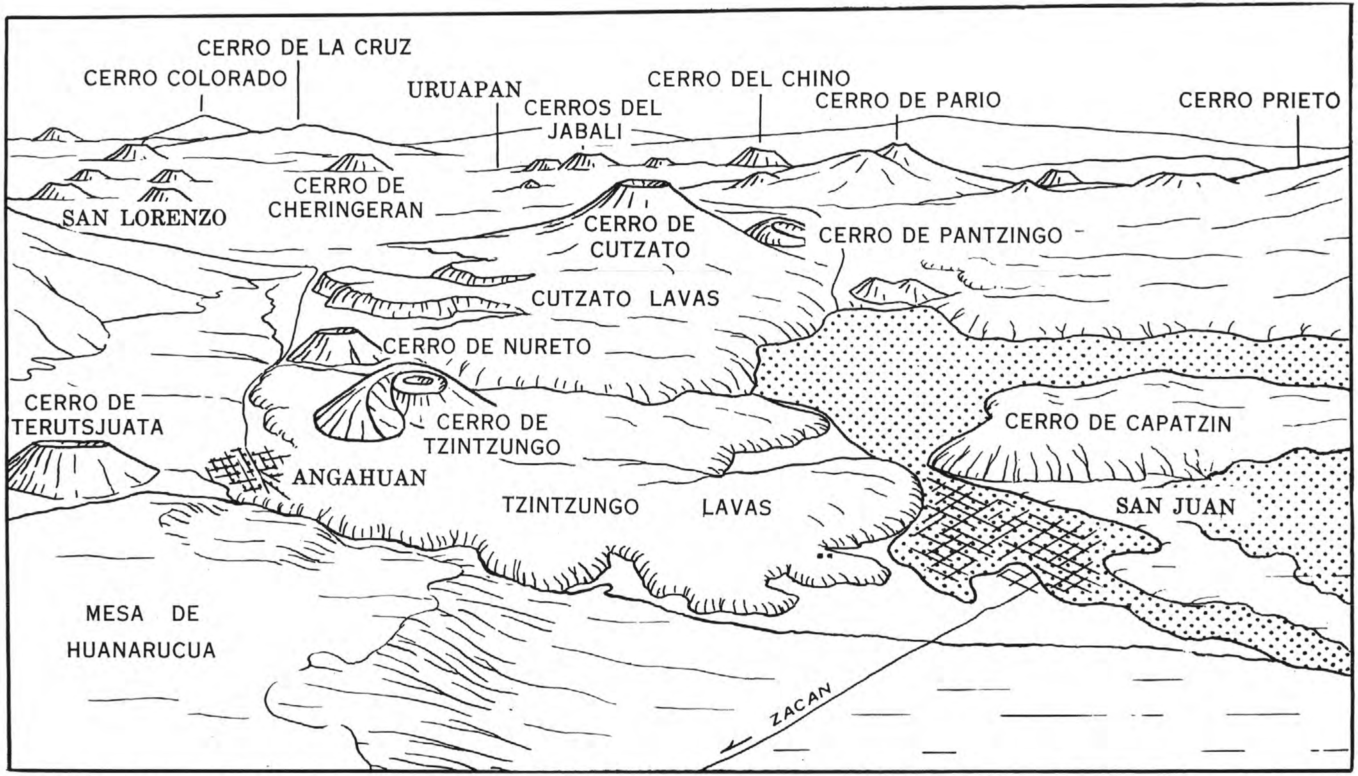


FIGURE 80.—Cerro de Tzintzungo, Cerro de Cutzato, and adjacent cones. View looking approximately eastward. The stippled area is covered by lava from Parícutin volcano (to August 1947). In left foreground, the andesitic lava of Huanárucua. Photograph above (p. 200) by the Compañía Mexicana Aerofoto, 1934.

During the closing stages of the growth of these cones, thick flows of scoriaceous and blocky, autobrecciated lavas issued from fissures around the base. The road cuts between Angahuan and San Juan Parangaricutiro expose some of these in section, showing a jumble of angular blocks in a matrix of rubbly and sandlike debris formed by decrepitation of the lava as it advanced. The flows underlie Angahuan and extend westward to form the bluffs overlooking San Juan Parangaricutiro and that on which Casa Cuezeño stands. The first flows moved to the east and south, but only for a short distance; the longest and last flow moved westward from the aforementioned breach on the flank of the cone.

Many small hillocks and ridges diversify the surfaces of the flows, especially near Angahuan. Some of these may be miniature scoria cones or large, dilapidated hornitos; others may represent parts of older flows rafted downstream by younger flows injected beneath them.

Although the lavas vary in texture, most of them are characterized by abundant phenocrysts, not only of augite and olivine but also of plagioclase. In fact, no other olivine-bearing basaltic andesites in the entire region are as plentifully charged with porphyritic feldspar.

A short distance to the east lies the smaller cone of Nureto. Its slopes are much more modified by erosion, and its crater has been replaced by a flattish top. The flows erupted from this source are of limited extent and poorly exposed. In the valley separating the Nureto from the Tzintzungo cone, ash has accumulated to depths of more than 100 feet, and it is from this valley fill that the large spring that formerly supplied San Juan Parangaricutiro issues.

Examination of ash profiles shows that the flows of the Tzintzungo cone are much younger than the andesite of Huanárucua and were erupted after the lavas of Nureto and Cutzato. They are, however, slightly older than the adjacent cinder cone of Terutsjuata.

CERROS DE CAPACUARO

By far the most voluminous outpourings of lava within recent times are those from the vent that lies between 4 and 5 miles east of the village of Capacuaro (fig. 81). A large conical mound rises over the vent, but whether this is a protrusion of viscous lava or consists of fragmental ejecta is not known.

The area inundated by flows from this source approximates 60 square miles, and the average thickness of the lavas is not less than 200 feet. Accordingly, more than 2 cubic miles of lava were discharged. By comparison, Parícutin erupted only about a sixteenth of a cubic mile of lava during the first 5 years of its history. Of special note is the fact that the lavas from Capacuaro do not consist of basalt or basaltic andesite like most of the recent lavas of the region but of glass-rich hypersthene andesite having a composition not markedly different from that of the andesite of Tancítaro.

Among the numerous flows of the Capacuaro volcano the largest deserves particular mention. This spread southward from the vent for about 12 miles. In places its width is almost 2 miles, and for most of its course it measures a mile across. Not only is it exceptionally long, but the steep margins rise to heights of 250 feet. Figure 82 gives an impression of the morainelike levees that confine the medial portions of the flow. Other massive flows spread westward to the village of Capacuaro and northward to the vicinity of Arantepacua; these also terminate in impressive blocky fronts up to 200 feet in height.

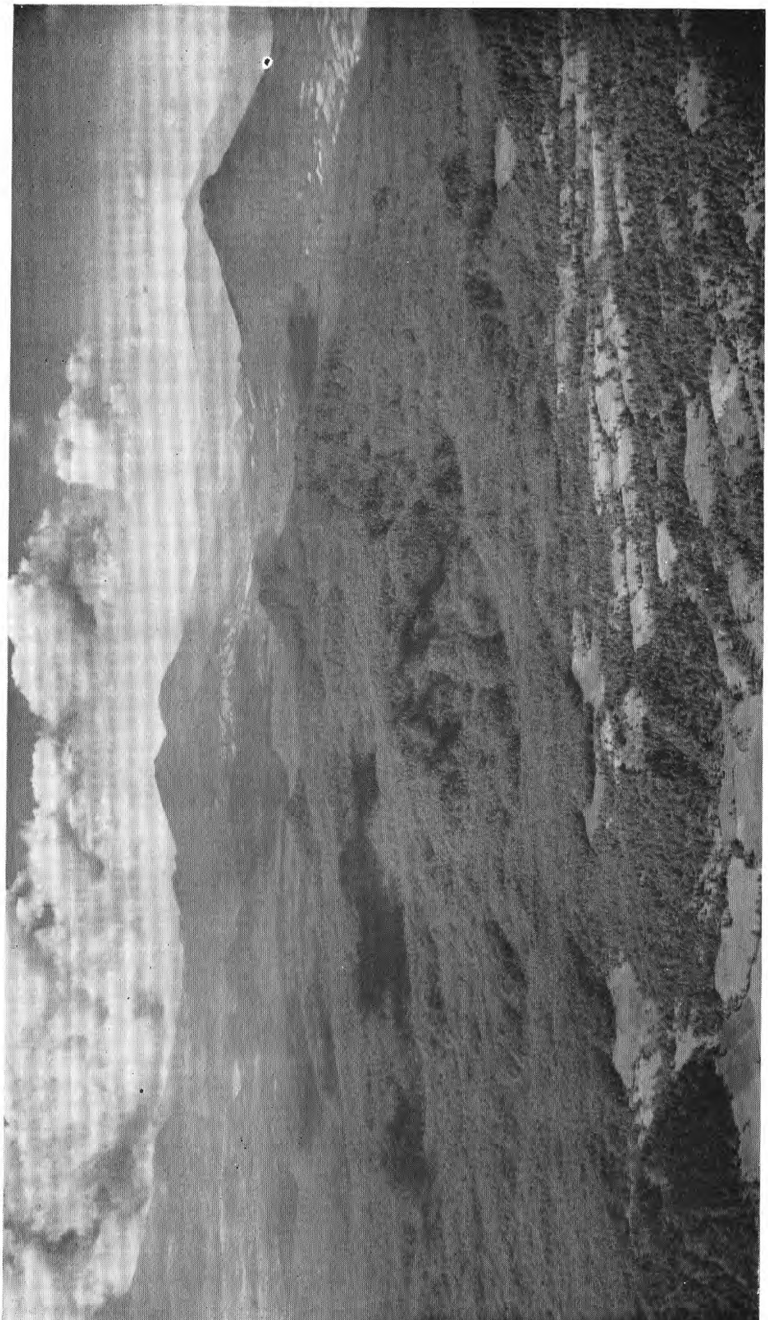
As might be expected from their high glass content, all the flows are true block lavas. Their upper parts consist of a jumble of smooth-faced blocks, many more than 6 feet across, loosely bound together by a rubble of comminuted lava chips. Downward the blocky crust grades into brecciated lava which merges in turn into massive andesite below.

Although heavily forested, the lavas are free from all but a thin, patchy cover of ash. Hence they are younger than all the cinder cones in the immediate vicinity. Their surface features are so well preserved that it seems safe to say that the flows were erupted either within the present or the preceding millennium.

CERRO DE CAPATACUTIRO

The youthful cone of Cerro de Capatacutiro lies close to the western base of Cerro del Aguila. From a breach in the western side, several flows of basalt descended toward the Mexico City highway. The earliest ones spread as far as Paracho Viejo; the later ones encircled the cone of Sicapen and flooded the valley north of the Cerros de Los Hornos (fig. 77).

The lavas of Capatacutiro are the least siliceous of any in the Parícutin region. They are coarse-grained olivine-augite basalts, and except for thin skins of glass they are entirely holocrystalline. In many places they exhibit crude pahoehoe forms, and their surfaces are marked by pressure ridges and collapse depressions caused by foundering of the roofs of tunnels. Here and there miniature lava tubes are still to be seen. No other flows within the area show these features; all other basalts and basaltic andesites are of the blocky or aa type.



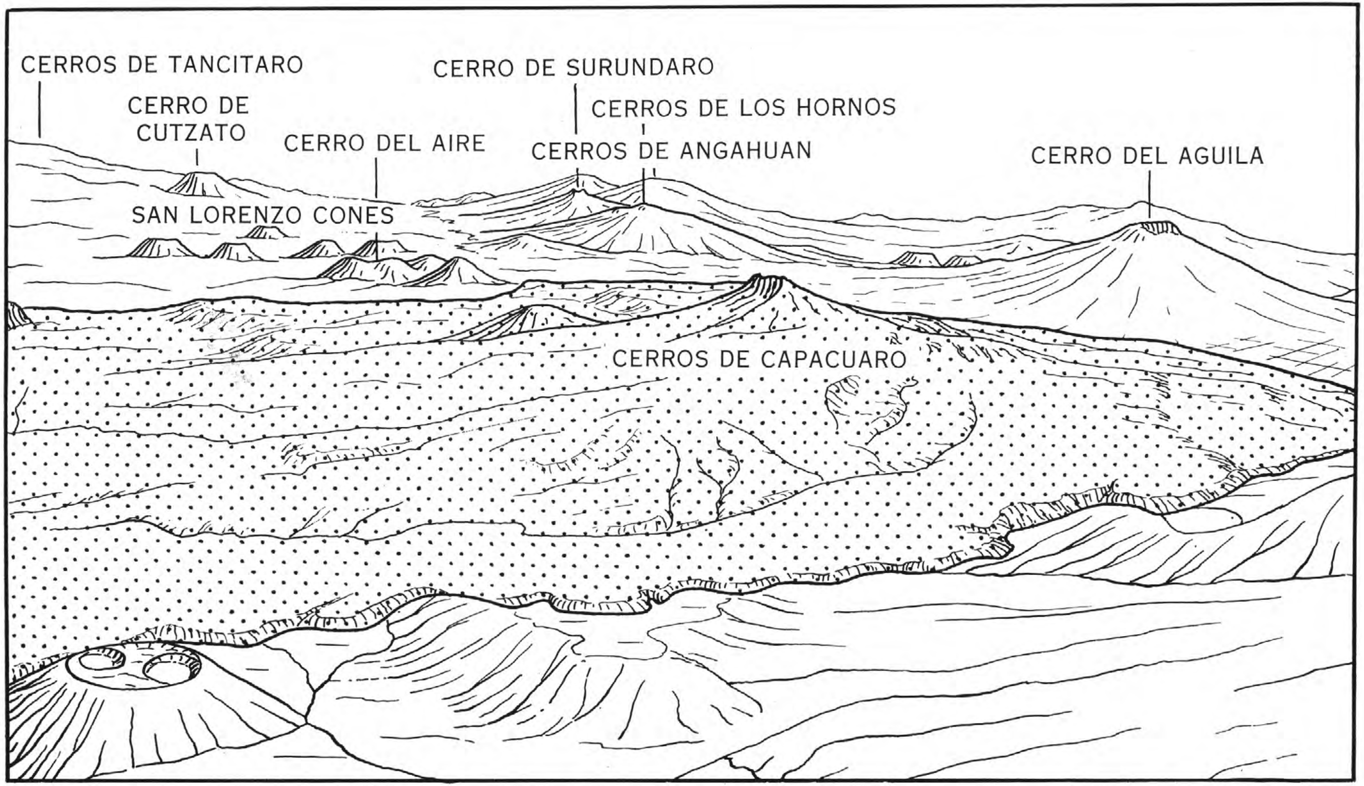


FIGURE 81.—Cerros de Capacuaro from the east. Area covered by the recent andesite flows of Cerros de Capacuaro is shown by stippling. Beyond lie the older andesitic volcanoes of Cerro del Aguila and Cerros de Angahuan and Cerros de Los Hornos; also the young andesite cone of Cerro de Surúndaro. View looking west. Photograph above (p. 204) by the Compañia Mexicana Aerofoto, 1934.

FIGURE 82.—Great flow of andesite from Cerros de Capacuaro, as seen from the southeast. The flow is more than 10 miles long and locally more than a mile wide. Note the marginal levees. In the foreground the flow is crossed by the railroad to Mexico City. To the left (west) lies Cerro Colorado, composed of iddingsite-rich basalts, and, behind it, Cerro de La Cruz, composed mainly of andesitic lavas. Both peaks are erosional forms cut in the Zumpinito formation. The intervening valley is occupied by recent flows of olivine basalt. Photograph by the Compañía Mexicana Aerofoto, 1934.

The excellent state of preservation of the features just mentioned is enough to indicate that these flows are among the youngest of the Parícutin region. However, they are older than the explosive eruptions that formed the nearby cones of Cumbuén, Pelón, and Paracho Viejo, and they are partly overridden by the lavas of the Surúndaro volcano.

CERRO DE SURUNDARO

The eroded eastern slopes of the Angahuan volcanoes are buried by widespread sheets of recent lava that form a malpais difficult to cross. These accumulated to build a broad, flattish, shield-shaped volcano around the summit cinder cone of Surúndaro (fig. 83). Because the flows emptied into the depression between the older volcanoes of Angahuan and the Cerros de Los Hornos, they were obliged to spread chiefly to the north and south. In the former direction they extended for about 5 miles, and near their snouts they eddied round the semicircular butte known as Loma Colorada. This peculiary shaped butte, which is approximately 300 feet high and has a flattish top, appears to be an old scoria cone downfaulted on its southern flank. A short distance to the southeast, the lavas of Surúndaro also eddied round the youthful cone of Cerro de Los Amoles and spread over the front of the olivine basalts erupted by Cerro de Capatacutiro.

Southward the lavas extended as far as San Lorenzo, near which they were deflected in their advance by another cinder cone.

Despite their wide extent, the flows of Surúndaro vary little in composition and texture. All are dark, blocky to scoriaceous lavas typified by a glass-rich matrix and an abundance of porphyritic olivine. In the field they would be classed without hesitation as olivine basalts, yet chemical analysis shows them to be andesites. As to their age, they are younger than the cone cluster of San Lorenzo and the basalts of Capatacutiro, and probably they are also younger than the andesites of Cerro de Capacuaro. Only the last flows of Cerro Prieto and the Jabalí cones and those now issuing from Parícutin are more recent.

CERRO PRIETO

The symmetrical, shield-shaped volcano of Cerro Prieto lies at the eastern foot of Cerros de Tancítaro (figs. 75, 85). Impeded on three sides by the opposing slopes of Cerros de Tancítaro, Cerro de Tzirapan, and the Cerro de Pario cones, the lavas discharged from the central vent of Cerro Prieto spread mainly to the south and southeast. These flows were augmented by others that issued from three parasitic cones. From the southernmost parasite, a narrow tongue of lava

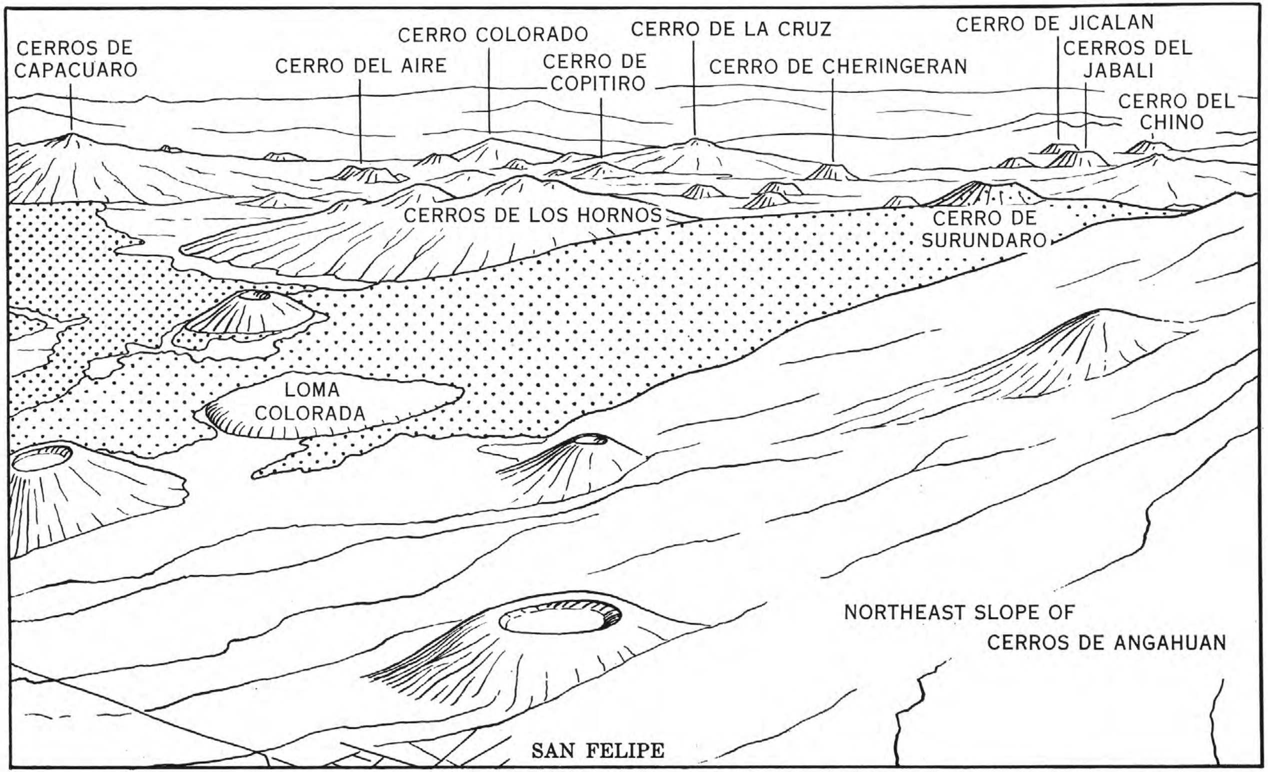


FIGURE 83.—Cerro de Surúndaro from the northwest. The young andesitic lavas of Cerro de Surúndaro, shown by stippling, lie between the older andesitic volcanoes of Cerros de Angahuan and Cerros de Los Hornos. The youthful andesitic cone of Cerros de Capacuaro appears in the distance, on the left. Photograph above (p. 208) by the Compañía Mexicana Aerofoto, 1934.

moved for 3 miles down a steep-sided canyon cut in the beds of the Zumpinito formation before coming to a halt in the flats near Santa Catarina. Hardly less impressive are several blocky flows that ran down other valleys toward Los Lobos.

The earliest and longest of the flows of Cerro Prieto were those that extended to Los Conejos. These are thickly covered with weathered ash. On the other hand, most of the later flows, which are confined to the upper flanks of the volcano on the south side and descend to the flats of Teruto on the opposite side, are only patchily covered with weathered ash, and some are so recent that they are mantled by no more than the thin veneer of ejecta from Parícutin. The surface forms of these younger flows are strikingly preserved; the fronts of successive flows stand out distinctly, and marginal levees and median gutters are well defined. Both in appearance and composition the lavas are almost identical with those of Parícutin; all are dense, vesicular, blocky, olivine-bearing basaltic andesites.

The cinder cone capping the lava shield had already ceased its explosive activity before most of the flows were extruded; hence its exposed top is probably only part of a much larger cone that began to grow early in the history of the volcano.

CERROS DEL JABALI CONE CLUSTER

A particularly youthful cluster of cones is to be seen a few miles northwest of Uruapan (fig. 84). Surrounding it is a rugged malpais of lava, some of which is of such recent origin that it supports only a scant cover of vegetation. Indeed, the last flow, a tongue of black, barren lava skirted by the road between Cerro del Chino and Los Conejos, may well have been erupted within the last century. Marian Storm (1945, p. 340) records a conversation with the Tarascan Indian who cultivated the corn patch in the crater of Cerro del Chino in the following words:

> * * * When the old people of my family were little this Hill of El Chino burst open and tons of mud poured out. Then freezing cold came over all this country; the animals in corral died of it. Snow fell, but ashes covered the land as well, shutting out the sun, and plants withered and trees lost all their leaves. We often tell again the story of those times. * * * Look where dark, hot rivers moved down El Chino on this side and stood still in what must have been a pretty valley, to make that malpais!

If this account is interpreted in the light of geological evidence, it seems clear that the informant was mistaken in referring to an outburst of Cerro del Chino, for the lavas from that cone are covered to a great depth with weathered ash. It is far more likely that the Indian referred to the final explosions of one of the Cerros del Jabalí cones and to the black tongue of lava mentioned above which abuts against the base of Cerro del Chino. No one seeing the Jabalí cones can doubt that they are younger than Cerro del Chino, for their slopes are still only slightly scored by erosion and the cinders that form them are scarcely decomposed. Considering the climate of the region and recalling how quickly vegetation reoccupied the country devastated by Jorullo in 1759, one cannot escape the view that several of the Jabalí cones may have erupted within the last few centuries. The surprising thing is that the people of the town of Uruapan preserve no legends concerning them.

The area covered by the flows of the Jabalí cones approximates that inundated during the last 5 years by Parícutin. They poured over the southeast slopes of Cerro de La Alberca from five closely spaced cones. The largest of these, Jabalí itself, rises to a height of about 350 feet. Cerro de Sapien, a short distance to the east, and the southernmost cone are slightly smaller; the other two are merely low mounds of scoria.

The oldest flows erupted by these vents are mantled with rotten yellowish ash from a few inches to several feet in thickness; hence they form cultivated islands and grassy patches between the younger flows whose thin and patchy cover of less weathered ash supports only a light growth of ferns, cacti, and pines. For the same reason, the older flows are easy to cross, whereas the younger ones make a blocky wilderness difficult of access. Despite the variability of the ash cover, however, the entire activity of the Jabalí cones may have taken place within a few centuries or a few millennia at most. Much greater variation in the depth of ash is to be seen on the flows now being discharged by Parícutin.

Among the first lavas of the Jabalí cluster are those exposed in the gorge of the Río de Cupatitzio where it runs through the national park on the outskirts of Uruapan. In this part of its course the river is floored by spheroidally weathered olivine basalt, perhaps derived from Cerro de La Alberca. Resting upon this is a layer, up to a few feet thick, of thoroughly decomposed clayey ash. Above this is a flow of columnar basalt, undoubtedly from one of the Jabalí cones. The copious springs that gush from the west bank of the Cupatitzio gorge, giving sudden birth to a full-fledged river, issue from the contact of the columnar lava with the underlying clayey ash.

All the flows from the Sapien cone are heavily blanketed with yellow ash. The last of them broke from a breach in the east flank of the cone, a short distance from which is a large mound of lava that represents a domical accumulation over a separate vent.

The youngest flows from the main Jabalí cone escaped from fissures close to the base, one on the north and the other on the east side. A large stream flowed from the northern fissure, spreading eastward for about 3 miles. Close to the outlet a spectacular lava gutter, between

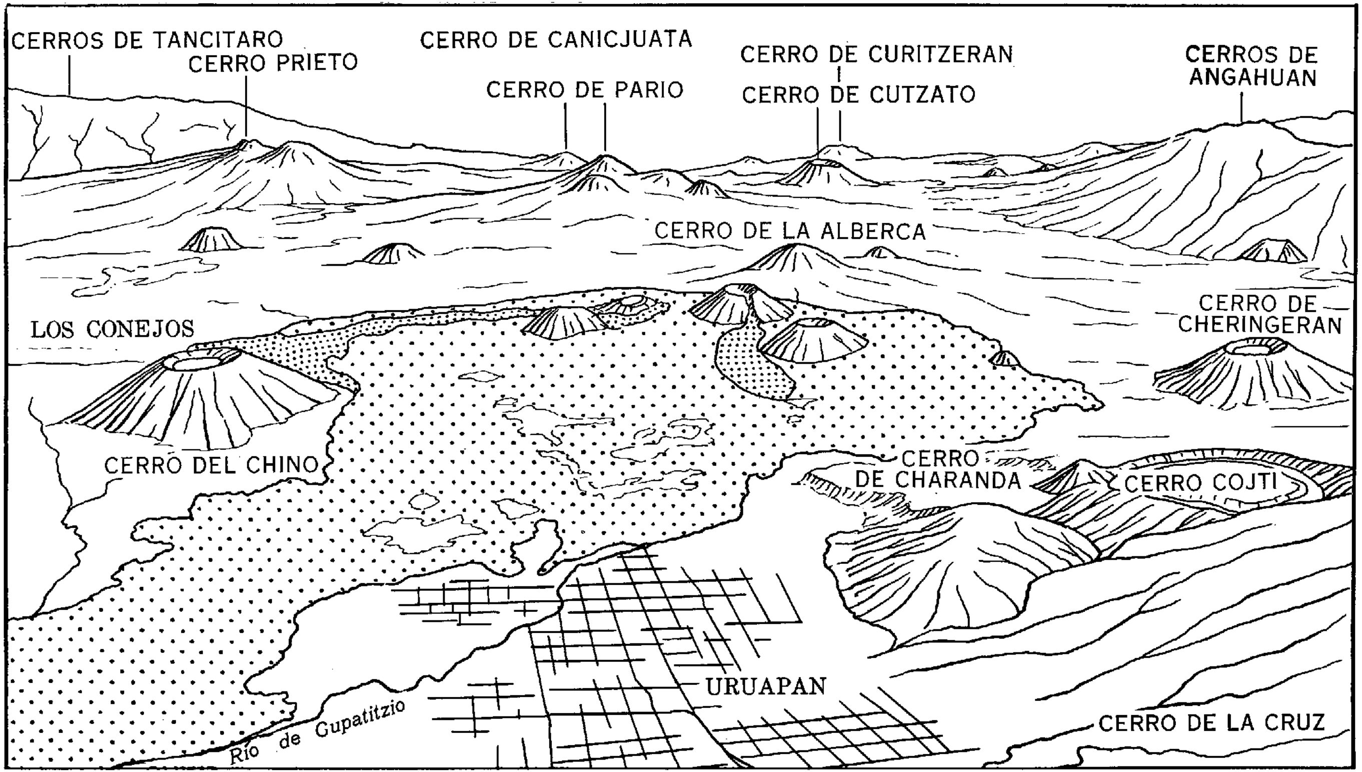


FIGURE 84.—Cerros del Jabalí cone cluster and its lavas, looking west over Uruapan. Older flows of the Jabalí cones are shown by light stippling; younger flows, by darker stippling. The flow that descends to Los Conejos may be less than a century old. The "Ringwall" and central lava mound of Cerro Cojti may be seen on the right. The eroded andesitic volcanoes of Cerros de Tancítaro and Cerros de Angahuan appear in the distance; between them lie younger cones and flows of basaltic andesite. Photograph above (p. 212) by the Compañía Mexicana Aerofoto, 1934.

150 and 200 feet deep and up to 250 feet wide, is bordered by precipitous walls. Smaller gutters have been observed on many flows of the Parícutin volcano where early congelation of marginal levees confines the moving currents to a central channel, the level of which is lowered by drainage as the supply at the vent becomes exhausted. Following this flow, lava escaped from the fissure at the east base of the Jabalí cone. Its extent is shown on the map (pl. 8). Here also the source is marked by a lava mound and central gutter, in this case of smaller dimensions. Both these late flows are exceptionally thick and have steep fronts up to 250 feet in height. Their surfaces consist of a litter of smooth-faced blocks of dense, glass-rich basalt stippled with iridescent olivines.

By far the largest of the younger flows of the Jabalí cone cluster is one that issued from fissures at the foot of the lowest and westernmost cone. This moved first southward and then eastward for more than 6 miles, descending to the gorge of the Rio de Cupatitzio near Jicalán. The roads linking Uruapan with Jicalán and Los Conejos cut across it, revealing the scoriaceous, rubbly, oxidized character of its interior.

The last flows of the Jabalí cones, the malpais negro to which Marian Storm's account almost surely applies, also issued from the foot of the westernmost cone. Its limits are depicted on the map (pl. 8). Probably at the same time, a short tongue of lava broke from a fissure at the east base of the same cone, piling up in the valley that separates it from the foot of Jabalí itself.

Fully three-quarters of the visible lavas erupted by the five Jabalí cones were discharged after the cones themselves had ceased their explosive activity. If all five cones were not formed simultaneously, they certainly grew in quick succession. The Sapien cone was the first to become extinct, but the order in which the others expired has not been determined. More thorough study of the cluster is much to be desired.

The lavas of the Jabalí cones vary so little in texture and mineral content that it is impossible to distinguish between specimens from adjacent flows or from different parts of the same flow, yet chemical analyses show that the most extensive flow is an olivine basalt, whereas the youngest is a basaltic andesite. Only additional analyses will indicate whether there is a regular sequence.

Despite the recency of the final flow, no signs of solfataric activity remain in the vicinity.

CONES ON THE WEST AND SOUTH FLANKS OF CERROS DE TANCITARO

As far as was possible, the volcanoes of the Parícutin region described in the preceding pages were discussed in the order of their formation. The relative ages of those to be referred to in this section are uncertain, since they were examined only in a cursory way.

Mention has already been made (p. 180) of the fans of bouldery debris, the products of lahars or volcanic mudflows, that spread for miles beyond the foot of Cerros de Tancítaro toward the northwest, west, and south. Similar deposits of more limited extent may underlie the cones and lavas near Parícutin. The oldest of these laharic deposits was laid down during the growth of Tancítaro itself, but it was not until discharge of ash from the encircling cinder cones began to accelerate erosion that most of them were formed. Today the fans near Peribán are being rapidly enlarged as an indirect result of the activity of the new volcano.

Evidence that the fans were developed chiefly during the period of basaltic eruptions is to be seen in the canyons along the west and south sides of Cerros de Tancítaro, where flows of olivine basalt and layers of basaltic ash are interbedded with the bouldery detritus. Around Peribán the detritus consists mainly of andesitic rocks derived from Tancítaro; locally it is interbedded with basaltic ash and tongues of lava. To the south, on the wooded Cerro de Parástaco, is a cluster of eroded cinder cones surrounded by dark, vesicular, olivine-bearing basaltic andesites, some of which interfinger with tuff breccias and bouldery sediments. The four largest cones stand almost in line, suggesting growth over a common feeding fissure that trends slightly north of west.

Near the village of Apo rises an exceptionally large cinder cone with a small parasite at its northwest base. Wide sheets of olivine basalt poured westward from these vents, and Apo itself is partly built on one of them. The adjacent country is buried to depths of more than 50 feet with weathered, yellowish-brown ash erupted from the same sources.

Where the road crosses the first gorge south of Apo, the bouldery fans are composed chiefly of basaltic debris and are interbedded with layers of basaltic ejecta and lava. Still farther south are two conspicuous mesas surrounded by alluvial fans, detached a short distance from the foot of Cerros de Tancítaro. Rare exposures beneath the ubiquitous mantle of decomposed ash suggest that these mesas were formed by viscous effusions of basaltic andesite, one from a fissure and the other from a cinder cone at its eastern end.

Around the village of Tancítaro and Rancho de Codémbaro the bouldery fans are particularly large, and they are rapidly burying the youthful cinder cones nearby. A short distance south of the former village is an extensive field of blocky lava, probably basalt. Unfortunately, circumstances prevented a close examination of the field, but the barren appearance and remarkably fresh aspect of its surface suggest that the lava may have been erupted within the last few centuries.

Turning to the east, along the south flank of Cerros de Tancítaro, the trail to Araparícuaro first crosses a broad apron of fanglomerate and then passes over tongues of vesicular olivine basalt related to the small cinder cones to the north. From Araparícuaro to the gorge of the Río del Fresno the trail climbs over a hummocky highland of basaltic lava built by effusions from Cerro de la Alberca and adjacent vents. The successive flows, with their gently sloping tops and steep fronts, form a giant staircase leading to the foot of Tancítaro. Many of these flows and the parent cones are only slightly modified by erosion, but the oldest ones are to be counted among the first of the post-Tancítaro lavas. For instance, near the top of the gorge of the Río del Fresno, on the west wall, is a flow of pale-gray holocrystalline basalt unusually rich in olivine, erupted so long ago that the river has incised a channel below it to a depth of about 150 feet.

From the Río del Fresno eastward the trail passes onto the underlying Zumpinito formation until it reaches Santa Catarina, where it climbs onto the recent flow of basalt erupted by Cerro Prieto (pp. 207–208).

CONES AND FLOWS NEAR PARICUTIN VOLCANO

Nowhere along the periphery of Cerros de Tancítaro is the cluster of cinder cones denser than in the vicinity of the new volcano. Although these cones vary widely in age, so that the periods of their activity overlap those of most of the "younger" volcanoes discussed in the preceding pages, they are here considered together in order to bring out more clearly the setting of Parícutin itself.

In attempting to date the cones near Parícutin on the basis of the degree of dissection, it must be borne in mind that erosion was greatly accelerated by the ash falls attending their growth. Account must also be taken of the torrential character of the rains in this region. During the wet seasons the volume of the streams increases a thousandfold. Moreover, as Segerstrom (1950) has emphasized, 90 percent of the summer rains fall in periods of no more than 30 to 60 minutes' duration. At times 2 inches of rain may fall in as many hours. As a result, loose ash is rapidly swept into the canyons to form torrents of great erosive power. In addition, the protective cover of vegetation is destroyed by the eruptions, and the water-soaked ash, even on gentle slopes, is subject to large-scale creep and recurrent slides. It is enough to witness the havoc caused by a single summer storm to be convinced that the deepest gullies on the oldest cones may have been excavated in a few thousand years. Many of the younger cones must have been active within the present millenium, and perhaps Loma Larga and the three Jarátiro craters ceased activity no more than a few centuries ago. Why the Tarascan Indians have no legends concerning these eruptions is difficult to understand.

On the map, plate 9, the cones near Parícutin are divided into two groups, an older one comprised of cones that are deeply dissected and devoid of summit craters and a younger one in which the cones and craters are well preserved.

OLDER GROUP

Among the oldest and largest of the cones near Parícutin are the three Cerros de Zirosto, the biggest of which is Cerro de La Máscara. Long, thick flows of gray, olivine-rich basalt issued from the feet of these cones to pour down the valleys of the Río de Itzícuaro, Río de Xundan, and Río del Agua Blanca at least as far as Peribán and San Francisco. In the canyon walls of the Río del Agua Blanca they rest on bouldery laharic deposits and are overlain by more than 100 feet of weathered basaltic ash. Elsewhere they are likewise heavily blanketed with ash, within which several soil horizons may be recognized. Similar olivine basalts flowed down the Itzícuaro valley past Barranca Seca from the coeval cone of Tiripan.

A short distance south of Parícutin rise Cerro de Camiro and Cerro de Tzirapan, two eroded cones of approximately the same age. The crater of Cerro de Camiro has been obliterated, and the flanks are deeply cut by ravines. Lavas from the base of the cone form a pedestal no less than 800 feet in thickness. Despite their large volume, however, the Camiro flows spread only a few hundred yards to the west, coming to a halt at the edge of Llano de Teruto. Northward they stretch for about a mile to Cerro de Nuréndiro at the margins of the Parícutin lava field. Clearly they must have been extremely viscous. No chemical analyses have been made, but the microscope shows them to be olivine-poor, hypersthene-rich lavas, and if they are not true andesites they are surely not less siliceous than basaltic andesites. Other thick, olivine-poor flows, possibly andesites, form Mesa de Cocjarao; these escaped from concealed fissures near Cátacu.

Cerro de Tzirapan consists of a principal cone and a parasite. The former rises about 600 feet above the encircling flows, most of which moved to the south and east through a breach in the flank. Probably the activity of this cone began shortly after Camiro had expired.

East of Tzirapan, in the region extending from the foot of Cerro Prieto northward to Cerro de Curupichu, all the lavas are basaltic andesites. They form a series of north-trending ridges with gently sloping, hummocky tops that descend in steps at the snouts of successive flows. Presumably they issued from Jurítzicuaro and adjacent cones after the last flows of the Pario volcano but before those of Cutzato.

Not far to the north of Parícutin is a ridge of lavas capped by Cerro de Jarátiro, Cerro de Equijuata, and Cerro de Capatzin (fig. 85). Most of this ridge has been submerged by the lavas of the new volcano. The northern end, from Cerro de Equijuata to Cerro de Capatzin, runs north for about a mile and is bounded by steep sides that rise between 300 and 400 feet above the adjacent flats. It consists of olivine basalts with or without basaltic andesites devoid of porphyritic feldspars. Contrasted with other lavas in the vicinity, these are much less vesicular, and it may be that this feature, coupled with the absence of interbedded ashes, accounts for the fact that the topographic ridge is also a ridge of high gravity values (Barnes and Romberg, 1948). The lack of craters and scoria cones on the crest suggests that Cerro de Capatzin and Cerro de Equijuata, together with the two small peaks west of the latter, represent domical accumulations of the last-extruded viscous lava over the feeding vents.

The saddle between Cerro de Equijuata and Cerro de Jarátiro is now buried by flows from the Parícutin volcano, but as late as 1945 northeast-trending ridges of oxidized and autobrecciated olivine basalt were to be seen there, separated by steep-walled, narrow depressions resembling lava gutters.

During the present survey, the Jarátiro ridge was so thickly covered by ash from Parícutin volcano that no exposures of lava were visible. At its eastern base was a perfectly preserved, almost circular crater, approximately 600 feet across at the rim and about 150 feet deep. In December 1944 lava from Parícutin poured over the rim and cascaded to the floor. Since then the crater has been almost completely filled. Two smaller craters, one 400 feet to the south and the other 800 feet to the southeast, were buried by lava from Parícutin at an earlier date. Their positions are indicated in plate 9, and the topographic map made by Segerstrom (1950) shows their forms. All three craters are much younger than the lavas of the Jarátiro ridge through which the largest was blasted; indeed, they were probably produced by the last explosions preceding the outbreak of the new volcano.

Of the lavas now buried by the cone of Parícutin, all that can now be said is that they include basaltic andesites, fragments of which were blown out during the first days of activity.

A short distance to the west of Parícutin are five large, eroded scoria cones: Cerro de Canicjuata, Cerro de Corucjuata, Cerro de Cuaxándaran, Cerro de Turajuata, and an unnamed cone nearby. Their locations and forms are indicated on the map (pl. 8) and in the photograph (fig. 85). Even the smallest of these cones rises to a height of 400 feet, whereas the largest, Canicjuata, is between 800 and 900 feet in height. All are craterless and deeply incised by radial barrancas. They appear to have been formed in quick succession, Canicjuata and Corucjuata perhaps being the last to erupt. The flows from all five cones moved principally to the north and northwest, and, as far as sporadic outcrops permit judgment, they all consist of olivine basalts or basaltic andesites closely resembling those now issuing from Parícutin.

Much of the ash from this older group of cones has been stripped by erosion and carried into the valleys of the Río de Itzícuaro and its tributaries; much has been washed from the flanks of the cones to accumulate in the adjacent canyons to depths of as much as 300 feet. In one of these canyons, 1.8 miles northwest of Parícutin, Segerstrom examined a 97-foot section of ash within which he recognized nine weathered zones. These indicate that periods of explosive activity alternated with long intervals of rest, probably to be measured in centuries.

YOUNGER GROUP

In marked contrast to the denuded cones just enumerated are five smaller ones with craters still intact. These are Cerro del Pueblo Viejo, Loma Larga, Cerro de Huachángueran, Cerro de Cátacu, and an unnamed cone nearby. Cerro del Pueblo Viejo is the oldest of this group, but even its activity took place long after the cones of the earlier group had become extinct. Its crater has been breached on the north side by the sapping action of a large spring; Cerro de Huachángueran and Loma Larga have been breached to a smaller extent by the headward erosion of streams. Indeed, Segerstrom (1950) observed that the flanks of Loma Larga had not been appreciably gullied prior to the eruptions of Parícutin. Presumably, therefore, it was formed after all the others. Cerro de Cátacu and the neighboring cone are also very well preserved, and their shallow, saucerlike craters are hardly modified by denudation. The flows from all five cones spread northward. However, the youngest flows in the vicinity were not discharged from any of these cones but from a fissure at the base of Cerros de Tancítaro, a short distance west of Cerro de Cátacu (pl. 9). These issued in two gushes; the first sent a stream northward for about a mile, whereas the second, overriding the first, came to a halt a little closer to the source. Both ended with steep, blocky fronts up to 300 feet in height. Their tops are covered by 3 to 4 feet of weathered ash, perhaps blown from Loma Larga and Cátacu, and by 6 to 7 feet of ejecta from Parícutin. They are composed of dark, vesicular, olivine-rich basalt or basaltic andesite.

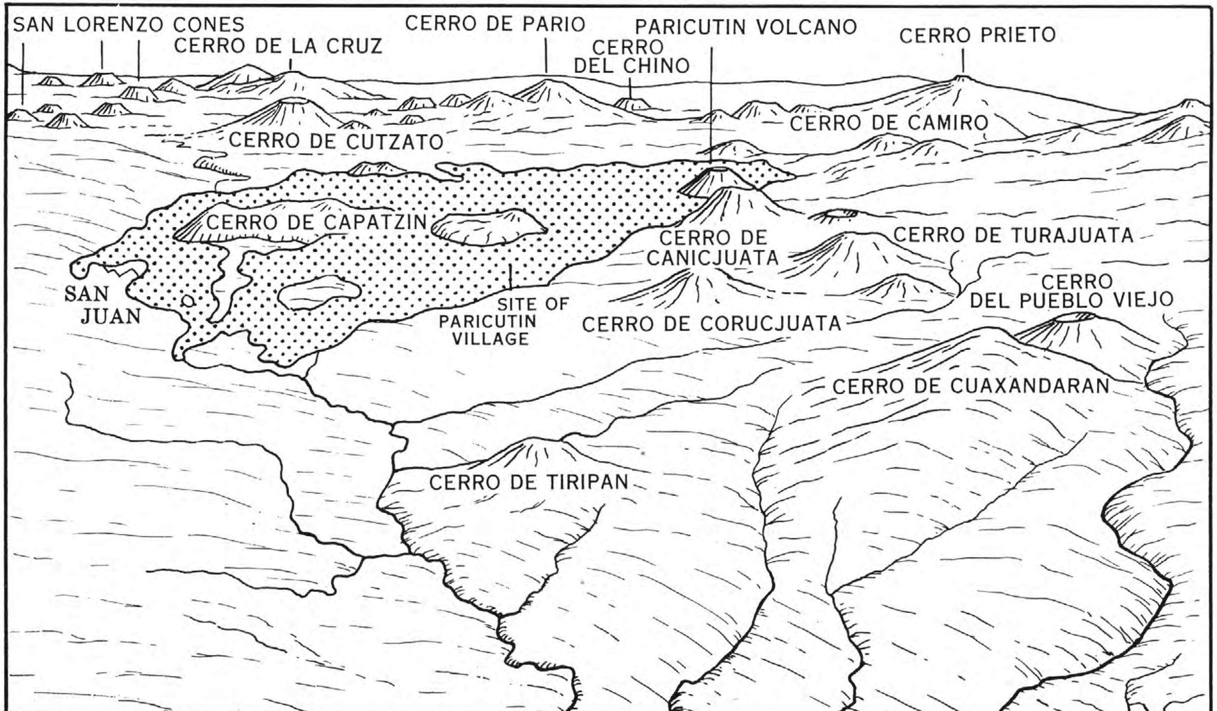


Figure 85.—Parícutin volcano and vicinity. Flows of Parícutin volcano, up to August 1947, shown by stippling. Photograph above (p. 220) taken in 1934, nine years before the birth of Parícutin, by the Compañía Mexicana Aerofoto.

Cerro de Lópizio, approximately 2 miles south of Parícutin volcano, is another youthful cone with a crater about 200 yards across, girdled by a low rim. From a breach in the eastern wall a flow of olivine basalt descended to Llano de Teruto.

Had the region close to Parícutin been studied before the cover of new ash became thick, a much clearer picture might have been drawn of the sequence of events preceding the present activity. This much, however, seems clear: The first eruptions in the vicinity took place from Cerros de Zirosto and Cerro de Tiripan, and the lavas discharged were olivine-rich holocrystalline basalts. Activity then shifted to Cerro de Camiro, from which viscous flows of olivine-poor, hypersthene-rich andesites or basaltic andesites were erupted. About the same time other viscous flows of olivine-poor lava escaped from fissures to the west to from Mesa de Cocjarao. A little later the double cone of Cerro de Tzirapan was formed, and perhaps the lavas of the Jarátiro-Equijuata-Capatzin ridge belong to the same period. Then five large cones—Canicjuata, Corucjuata, Turajuata, Cuaxándaran, and an unnamed cone—developed west of Parícutin, discharging flows of basaltic andesite. A long interval of quiet ensued. Subsequently the cones of Pueblo Viejo and Huachángueran were built. Cátacu and the unnamed cone nearby erupted next, and perhaps Lópizio was active at approximately the same time. The youngest cone to develop was Loma Larga, but the final eruptions prior to the growth of Parícutin were probably those that produced the three craters close to Cerro de Jarátiro, about a mile north of the new volcano. The lavas of all these younger cones are essentially similar to those now issuing from Parícutin itself.

PARICUTIN AND ITS FIRST FIVE YEARS OF ACTIVITY

For many years a small hole on the lands of Rancho de Tepicua had "emitted a pleasant warmth" (González and Foshag, 1947). The first signs of impending disaster were quakes on February 5, 1943. For 2 weeks they increased in number and intensity. On February 19, no less than 300 were felt (Trask, 1943). On the next day, Dionisio Pulido left the village of Parícutin to prepare his land for sowing. At 4 o'clock that afternoon, much to his surprise, he noticed that a fissure half a meter deep, trending slightly north of west, had opened there, and "in the hole the ground swelled and raised itself—2 or 2½ meters high—and a kind of smoke or fine dust—gray, like ashes—began to rise" (González and Foshag, 1947). Trees nearby swayed, and some, 30 meters from the hole, began to burn. When Dionisio's brother reached the spot at 6 p. m., "smoke" was rising from the hole, and low mounds of fine ash were beginning to accumulate. By 10 p. m. showers of incandescent rocks were visible from the village of San Juan Parangaricutiro. At 8 o'clock the next morning the volcano was already 10 meters high. By midday it had grown to a height between 30 and 50 meters. Later in the day the first flow appeared, escaping from a vent at the northeast base of the cone.

Thereafter the cone grew with amazing rapidity. By February 26 it was more than 160 meters high. Its explosive violence was awesome; the noise could be heard even in Guanajuato, 350 kilometers away. Every few seconds showers of glowing ejecta rose from the crater. Most of the bombs were a few feet across, but some measured 50 feet in diameter. Most of them were angular and smashed into fragments when they struck the ground; a few were tear-shaped, and some were fluid enough to flatten when they landed. Mixed with these clots of new magma were lumps of old andesite and plutonic rock torn from the walls of the conduit. Ash-laden clouds of vapor rose a mile or more above the cone.

On the twelfth day the volcano measured 1,500 feet across the bottom (Ordóñez, 1943), and lava had covered more than half a square kilometer. Explosive activity reached a climax on March 18; for a month the sky was turbid with dust. Heavy showers of ash fell on Uruapan, and early in April fine ejecta fell on Mexico City.

In mid-April a second crisis took place, and a new tongue of lava broke from the southwest base of the cone. On June 9 a slight change in the shape of the crater rim heralded a break; by the next morning the upper part of the cone had slumped and was being carried away on the crust of a flow that had escaped during the night. On June 14 a lava fountain burst out 300 feet below the crater rim, and a flow cascaded from it for several weeks, passing under the crusted flow of June 9 so as to upheave and float it downstream. During early July other flows were injected under earlier ones, carrying them along for as much as 1,200 feet (Ordóñez, 1947). At no other time in the history of the volcano has lava broken out part way up the flank of the cone; all other flows have issued from vents at or close to the base on the northeast and southwest sides.

The most violent period in the life of the new volcano was probably July and August of 1943. Lava then stood higher in the central crater than at any subsequent period. On June 19 it was within 50 feet of the rim (Trask, 1943). According to Foshag (1947), each flow was preceded by strong explosions that ended shortly before the lava issued; while the lavas emerged, explosions were relatively few.

On October 19, 1943, the activity of Parícutin diminished and a parasitic vent, Sapichu (fig. 86), opened at its northeast foot. For 79 days, until January 6, 1944, while Parícutin lay comparatively quiet, Sapichu erupted with vigor, building a cone 200 feet in height

864334—50——5

and discharging fluid lava northward to the base of Cerro de Equijuata. No sooner did Sapichu die than the parent cone renewed its violent activity. New vents opened on the opposite side, and the adjacent area was riven by fissures. For the next 3 years, until January 19, 1947, all the lavas emerged from closely spaced vents on this, the southwest side of the cone. Hardly did one flow stop before another broke from a new orifice close at hand.

By the end of the first year, Parícutin was approximately 1,100 feet high. The greatest discharge of fragmental ejecta certainly took

FIGURE 86.—Parícutin volcano from the south, April 1944. Parasitic cone of Sapichu at the northeast (left) base of the main cone; ash-covered flow of June 1943 at the northwest base. To the right (west) of Parícutin volcano, the denuded cone of Cerro de Canicjuata. Photograph by A. Brehme.

place during these first 12 months; since then effusion of lava has been the dominant process.

The flows that issued early in 1944 soon accumulated to build the so-called Mesa de Los Hornitos adjacent to the southwest vents. Most of the lavas moved first to the east and then northward around the foot of the cone, and many buried themselves by injection under older flows. During April, lava moved around the east side of the Equijuata-Capatzin ridge, then turned westward to reach the outskirts of San Juan Parangaricutiro in May. By the end of July most of the town had been buried. Subsequently the flows continued in the same direction for more than a mile before coming to a standstill in August. This flow that covered San Juan Parangaricutiro was the most voluminous of all the flows discharged by Parícutin volcano; its total length was about 7 miles.

In September 1944 another vent opened on Mesa de Los Hornitos close to the source of the flow that buried San Juan Parangaricutiro; spectacular lava cascades descended from it to inundate most of the village of Parícutin and spread beyond to unite with the lava of the San Juan flow near its snout (Bullard, 1947).

On November 7, 1944, the Ahuán vent opened, again close to the source of the flow that covered San Juan Parangaricutiro. The lava from this new orifice followed the same course, but it traveled a shorter distance, coming to a halt near the eastern foot of Cerro de Capatzin. Another flow broke from a nearby vent in February 1945, following the course of the September–October 1944 flow so far as to cover most of the village of Parícutin not previously inundated. Throughout this period explosive activity was irregular. At times the summit crater lay quiet for 24 hours at a stretch; at other times the explosions were almost as violent as at any previous period.

A succession of short-lived flows issued from the southwest vents during the remainder of 1945, throughout 1946, and until March 2, 1947. Some poured northward to Parícutin village and beyond; others moved around the south and east sides of the cone.

On January 19, 1947, when the activity of the southwest vents was diminishing, new vents developed on the opposite side of the cone, not far from Sapichu, at an elevation approximately 100 meters lower than that of the southwest vents. Slow but continuous effusions of lava issued from these northeast vents until October 1947, the flows moving northward along the west side of the Equijuata-Capatzin ridge. Then once more, as the activity of these vents waned, new ones broke open on the southwest side of the cone. From August to the close of 1947 these continued to emit slow-moving tongues of lava.

Such in brief has been the history of Parícutin during its first 5 years. Detailed accounts of its activity have appeared in the various publications listed at the end of this report. It may be appropriate, however, to summarize some of the principal features.

Explosive activity.—As stated already, most of the fragmental ejecta were expelled during the first 12 months. Comparison of the isopach map of the ash blanket made in May 1945 (Krauskopf and Williams, 1946) with that prepared in October 1946 by Segerstrom and here reproduced as plate 9 shows that the amount of ash added during the intervening 18 months was extremely small. By the latter date, the volume of ash was 0.65 cubic kilometer. Since then the increase has been slight. Thus far, therefore, Parícutin has repeated the history of most of the adjacent cones, its main explosive period occurring in the early stages.

At the close of the first year the main cone was already about 1,100 feet high. During the next 4 years its height increased by only a small amount. Meanwhile, the lower part of the cone was rapidly buried by lava. Between May 1945 and June 1947, while the rim of the crater rose only 140 feet, the visible height of the cone was reduced between 262 and 306 feet by accumulation of flows around the base (Wilcox, 1948a). If, as seems likely from the record of adjacent volcanoes, effusive activity continues increasingly to dominate over explosive discharge, the visible portion of the cone will be much further reduced. The present activity, therefore, suggests that the small cones that cap many of the neighboring volcanoes are not the result of weak concluding eruptions but are simply the exposed tops of large cones whose growth began at an early stage.

Apart from the foreign fragments of andesite and plutonic rock torn from the basement and the walls of the conduit, the pyroclastic ejecta consist entirely of olivine-bearing basaltic andesite either identical with the lavas or differing only in the degree of vesicularity and higher content of glass. Most of the lapilli and bombs are angular or subangular and were erupted either in a solid state or in an extremely viscous condition. At times more fluid clots have been expelled. The lateral variations of the ejecta have been studied in detail by Segerstrom (1950). Highly vesicular, pumiceous material has been thrown out at intervals, especially by Sapichu, but most of the larger fragments are dense, glassy types. No systematic variation in texture or composition has been detected.

Lavas.—These also have varied little in composition (table 3). All are olivine-bearing basaltic andesites. Typically they are of the aa type, varying from aa rubble and clinkers to massive aa, as defined by Jones (1946). The peculiar surface textures of the lava that buried the San Juan flow have been described by Ordóñez (1947), Bullard (1947), and Krauskopf (1948b).

Of particular interest has been the repeated injection of new lavas into and under older flows. These more or less sill-like injections have caused upheaval, doming, and extensive lateral displacements of old flows by younger ones. Where such injections have occurred, fumarolic activity has been especially long lived. For instance, the lava injected under the flow of June 1943 continued to emit fumarolic vapors for more than 3 years, and where the flow from Sapichu in late 1943 was injected early in 1944 by the San Juan lava there were extremely hot gas vents at the surface as late as 1945.

The areal extent of the lavas has not increased much since October 1944, but the thickness, especially near the cone, has continued to increase rapidly. By the close of 1947, the lava around the foot of the cone had reached a thickness of approximately 800 feet at the southwest base and 500 feet at the northeast base. From these places the thickness diminishes to between 20 and 50 feet around most of the periphery of the lava field. In October 1946, the total volume of the lavas was estimated to be between half and a third of the volume of the ash; that is, it amounted to about a quarter of a cubic kilometer. By the close of 1947, the total volume of ash and lava exceeded a cubic kilometer.

The rate of flow of the lava has varied with the gradient, volume, proximity to the source, gas content, and temperature. Krauskopf observed a typical flow in 1945 which moved at 6 to 15 meters a minute down a slope of 12° to 19° close to the source, whereas at its snout the movement was reduced to 45 meters a day on a 1° slope. Another flow moved at 0.7 meter to 8 meters a minute on slopes of 2° to 15° near the source, whereas the snout moved 100 meters a day down slopes of 5° to 6°, diminishing to a standstill as the supply at the source was cut off. Comparable estimates were made by Bullard (1947) on flows of 1944 and 1945.

As for the temperature of the lava, Zies (1946) recorded 1,110° C. in a flow in November 1944 at a distance of 3 miles from the vent. At the vent itself, he estimated that the temperature might have been close to 1,200° C. Krauskopf recorded vent temperatures of 1,026° and 1,060° C. during 1945—1,010° C. in lavas far from their sources. Bullard (1947) found temperatures of 1,043° to 1,057° C. at the vent of a flow in September 1944 and observed that a crust began to develop on the lava at approximately 950° C.

Satisfactory estimates of viscosity are difficult to make. Krauskopf (1948b) calculated that lavas near their vents have viscosities between 10^5 and 10^6 poises. Near the snouts of the flows it is hard to make an impression on red-hot lava with the blow of a pick. In later stages of advance the lavas move by shearing; there is nothing approaching turbulent flow even at the vents, only a slow laminar motion.

Primary sublimates from fumaroles on the lavas have consisted chiefly of ammonium chloride. By reaction with the lava, crusts of yellow, orange, and red iron-bearing chlorides have been produced (Foshag and Henderson, 1946). Krauskopf noted a predominance of HCl in gases from the lava vents and of SO_2 in those discharged by the summit crater during 1945. Incrustations of monoclinic sulfur were then seen in fissures within the crater. Where fumarolic activity is long continued, the lavas are considerably decomposed. In this connection, it is noteworthy that the older lavas of the region show little or no sign of such alteration. Beyond the confines of the flows from Parícutin there are no solfataras or hot springs, nor is it likely that any will develop after the new volcano dies.

Other features.—Emphasis should be placed on the observation made repeatedly by many observers that explosive activity can seldom be correlated closely with effusive activity. For a brief period in 1943, White (1945) noted a cyclic activity during which such a correlation could be made, but throughout most of the history of the volcano the summit crater appears to have behaved independently of the lava vents at the base of the cone. Sometimes an increase in intensity of explosive activity has preceded the opening of a new lava vent, but this has been far from a general rule. Krauskopf (1948a) has suggested an explanation for the erratic relations between outflow and explosions. At times the amount of water vapor discharged from the crater has been abnormally great in proportion to the amount of lava escaping from the basal vents. The presumption is that much of the vapor is derived from underground water, but proper interpretation of this phenomenon, which lies at the basis of an understanding of volcanism, must await more thorough studies.

No consistent correlation can be drawn between the activity of the volcano and either barometric pressure or tide-producing force, although, as Wilcox (1948a) has observed, sympathetic variations may exist for short intervals.

Finally, it should be pointed out that although the summit crater measures approximately 300 meters in diameter, the explosive vents within it are extremely small, seldom measuring more than a few meters in width. The position and number of these small vents have varied, but all tend to lie on the northeast-trending line connecting the lava vents on opposite sides of the cone.

PETROGRAPHY

ROCKS OF THE ZUMPINITO FORMATION

The following notes refer to the main rock types of the Zumpinito formation exclusive of the tuffaceous clays. For the sake of convenience the rhyolites are described first, then the andesitic lavas, and finally the basaltic lavas.

RHYOLITE TUFFS NEAR CALTZONTZIN

The upper part of the rhyolite tuff near Caltzontzin is a white, friable, pumiceous material devoid of stratification. About a third of a typical sample consists of clear, colorless, curved shards of glass and pumiceous shreds; an equal amount consists of impalpable glass dust clouded by specks of ore and blotches of limonite. Small lithic chips of pyroxene andesite comprise 3 percent of the volume. The remainder is made up of phenocrysts up to 2 millimeters in length. These are present in the following percentages by volume: calcic andesine, 17; quartz, 8; sanidine, 5; and biotite, 1.

Beneath this incoherent tuff and contrasting strongly with it are pink tuffs that are completely devitrified and intensely welded. In these, vitroclastic texture is only faintly discernible, the shards being flattened into subparallel streaks that wind around the phenocrysts in a manner suggestive of the fluidal banding of lava. Approximately 80 percent of the volume of a representative sample consists of cryptofelsite, in which some relic shards show replacement by fibrous quartz and sanidine. Approximately 10 percent is composed of sanidine phenocrysts, 2 percent of calcic andesine, 6 percent of quartz, and 1 percent of biotite. In the overlying tuff the mica is fresh and pseudouniaxial, but here it is deep red, is partly rimmed with magnetite, and has optic angles that range up to 15°. The welded tuff is characterized further by abundant tridymite in lenticular streaks parallel to the banding. The pink color comes from finely divided hematite dust, presumably, like the tridymite, a product of fumarolic vapors. These petrographic features corroborate the view gained by examination in the field that the tuffs were laid down by glowing avalanches of the Katmai type.

ANDESITIC LAVAS

In the mountainous country bordering the road to Apatzingán and along the trail joining Los Conejos with Tancítaro village, the dominant lavas are coarsely porphyritic pyroxene andesites similar to those that form Cerros de Tancítaro, to be described on pages 235–238. In brief, they are hyalopilitic to pilotaxitic lavas studded with zoned crystals of sodic bytownite-calcic labradorite up to 3 millimeters in length and smaller phenocrysts of augite and hypersthene. Olivine is present as a minor constituent in some flows; in others a little oxyhornblende can be found.

A markedly different type of andesite is widespread on Cerro de Las Ventanas. This lacks porphyritic feldspar. Between 85 and 90 percent of the volume is made up of a fluidal felt of sodic andesine microliths associated with granular ore, specks of augite, flakes of hematite, and interstitial cristobalite. The remainder is composed of oxyhornblende phenocrysts largely replaced by augite and ore.

A third kind of andesite forms the bulk of Cerro de La Cruz. In this, hypersthene preponderates over augite and the texture varies from hyalopilitic to vitrophyric. The analyzed specimen (table 1, analysis 14) is illustrated in figure 87*II*. Approximately 45 percent of the volume consists of plagioclase microphenocrysts up to 0.5 millimeter long, mostly ranging from An_{60} to An_{65} but occasionally

TABLE 1.—*Analyses of lavas from volcanoes near Paricutin*

[L. C. Pick, analyst, University of Minnesota]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Constituents																		
SiO_2	50.85	51.38	51.49	52.85	54.58	55.28	55.68	56.51	56.80	57.84	57.91	58.46	59.18	59.54	59.70	60.78	61.10	61.30
Al_2O_3	18.04	17.46	18.56	18.46	18.65	20.07	17.77	17.72	18.54	18.59	17.81	18.35	17.35	18.19	18.01	17.92	18.06	17.46
Fe_2O_3	2.72	1.24	2.38	1.72	1.41	3.05	1.91	3.50	1.88	2.98	1.60	2.20	2.67	1.98	1.75	.97	2.53	.97
FeO	6.19	6.41	6.57	5.58	5.54	2.89	5.07	3.07	4.50	2.83	4.36	3.30	2.99	3.19	3.39	4.00	2.31	3.67
MgO	5.73	9.13	5.63	6.06	5.00	3.11	4.94	5.48	5.03	3.50	4.86	3.37	4.33	3.45	2.89	2.55	2.56	3.11
CaO	9.10	8.95	9.56	8.85	8.39	8.00	6.78	7.17	7.06	6.70	6.60	7.00	6.39	6.81	6.04	5.83	4.89	5.75
Na_2O	3.59	3.03	3.23	3.56	3.45	3.69	3.65	3.78	3.98	3.90	3.65	4.03	3.70	3.61	3.66	3.62	4.25	3.41
K_2O	1.31	.54	.58	.86	.98	1.04	1.33	1.40	1.01	1.43	1.48	1.66	1.53	1.44	1.69	1.92	1.75	1.99
H_2O+	.10	.30	.29	.26	.37	1.27	.56	.20	.07	.54	.51	.40	.73	.93	1.45	.97	.90	.93
H_2O-	.05	.06	.11	.05	.08	.24	.24	.06	.04	.43	.20	.04	.06	.10	.16	.10	.55	.11
CO_2	------	------	------	------	------	.01	------	.01	.02	.02	------	.00	.01	------	------	.00	------	------
TiO_2	1.81	.89	1.22	1.10	1.02	.88	1.20	.85	.78	.82	.87	.72	.70	.73	.79	.75	.59	.71
P_2O^5	.43	.34	.19	.28	.45	.29	.70	.28	.23	.23	.24	.31	.21	.09	.23	.20	.20	.37
Cl	------	------	------	------	------	.07	------	.05	.03	.00	------	.07	.02	------	------	.02	------	------
F	------	------	------	------	------	.03	------	.03	.02	.03	------	.04	.01	------	------	.02	------	------
S	------	------	------	------	------	.02	------	.01	.01	.01	------	.01	.01	------	------	.02	------	------
MnO	.15	.13	.15	.13	.12	.10	.12	.11	.11	.09	.11	.10	.10	.09	.09	.09	.10	.08
BaO	------	------	------	------	------	.03	------	.05	.04	.06	------	.04	.05	------	------	.07	------	------
Total	100.07	99.86	99.96	99.76	100.04	100.07	99.95	100.28	100.15	100.00	100.20	100.10	100.04	100.15	99.85	99.83	99.79	99.86
Niggli values																		
si	125	119	127	134	147	162	158	156	159	177	169	178	181	188	198	207	211	207
al	26	24	27	27.5	29.5	35	29	29	30	33.5	30	33	31	34	35	36	37	35
fm	39	47	39	38.5	35.5	28	37	37.5	36	30.5	36	29	34	29	23	27	27	29
c	24	22	25	24	24	25	21	21	21	22	21	23	21	23	22	21	18	21
alk	11	7	9	10	11	12	13	12.5	13	14	13	15	14	14	15	16	18	15
k	.19	.11	.10	.14	.15	.16	.19	.20	.15	.19	.21	.22	.21	.20	.23	.26	.21	.29
mg	.54	.68	.54	.60	.57	.50	.59	.61	.59	.53	.60	.53	.59	.56	.51	.48	.50	.55
qz	−19	−9	−9	−6	+3	+14	+6	+6	+7	+21	+17	+18	+25	+32	+33	+43	+39	+47

1. Olivine-augite basalt from Cerro de Capatacutiro cone (95). On main highway, approximately 4 miles northwest of Capacuaro (fig. 88*E*).
2. Olivine-rich basalt. Main flow from the Cerros del Jabalí cone cluster (20). On road between Uruapan and Jicalán (fig. 89*A*).
3. Olivine-rich basalt (45). Near summit of Cerro Colorado (fig. 88*D*).
4. Olivine-rich basalt (63). Flow from Cerro de Tzintzungo, approximately 1 mile east of San Juan Parangaricutiro (fig. 88*C*).
5. Olivine-augite basaltic andesite (35). Lava mound near east base of Cerro del Aire (fig. 88*B*).
6. Hornblende andesite (113). East edge of Mesa de Zirimóndiro, approximately 1½ miles northeast of village of Tancítaro (fig. 87*D*).
7. Olivine-rich basaltic andesite (10). Thick flow from Cerro de Cutzato, 3 miles southeast of San Juan Parangaricutiro (fig. 88*F*).
8. Olivine-bearing basaltic andesite (121). South slope of Cerro Prieto, on trail between Tejamanil and Los Conejos (fig. 88*G*).
9. Olivine-rich basaltic andesite (23). Most recent flow from the Cerros de Jabalí cone cluster, approximately 1 mile east of Los Conejos (fig. 89*B*).
10. Hypersthene-augite andesite (79). Peña del Horno (fig. 87*A*).
11. Olivine-rich basaltic andesite (38). Cascada de Tzaráracua, Río de Cupatitzio (fig. 88*A*).
12. Pyroxene-hornblende andesite (91). Flow from Cerros de Capacuaro, on road between Capacuaro and Arantepacua (fig. 87*E*).
13. Olivine-bearing andesite (92). Cerro de Surúndaro near San Lorenzo (fig. 88*H*).
14. Augite-hornblende andesite (58). South edge of Mesa de Huanárucua, approximately 1 mile north of San Juan Parangaricutiro (fig. 87*C*).
15. Pyroxene andesite (65). Near north summit of Cerros de Angahuan (fig. 87*G*).
16. Hypersthene-augite andesite (90). Southeast slope of Cerro del Aguila (fig. 87*F*).
17. Hypersthene-augite andesite (111*A*). Summit of Cerros de Tancítaro (fig. 87*B*).
18. Hypersthene andesite (14). Near summit of Cerro de La Cruz (fig. 87*H*).

with rims of An_{55}. Oscillatory zoning is common, and the cores of many crystals are spongily replaced by glass. Prisms of hypersthene ($2V=80°$), of the same dimensions, make up about 15 percent of the volume. A few are enclosed by jackets of augite on the vertical faces. The rest of the andesite consists of brown glass relieved by acicular laths of calcic andesine, anhedral specks of augite, and minute grains of ore. Chemical analysis shows the andesite to be similar to those composing the Tancítaro, Angahuan, and Capacuaro volcanoes.

LAHARIC DEPOSITS

The tuff breccias of the Zumpinito formation include a wide variety of andesitic fragments with subordinate dacites and basalts. Most of the larger fragments in the deposits near Peribán and Los Reyes are of pyroxene andesite; in the deposits along the Río de Cupatitzio they consist chiefly of hornblende-bearing andesites. The fine matrix between the lapilli and blocks is crystalvitric tuff, mostly composed of broken chips of labradorite, hypersthene, and augite and shards of brownish glass.

BASALTS

The lavas of Cerro Colorado are subophitic to intersertal, olivine-rich augite basalts marked by extensive development of iddingsite.

The specimen illustrated in figure 88*D* is a coarsely crystalline variety from the summit of the mountain. Its chemical composition is shown in table 1. Micrometric analysis reveals the following percentages by volume: plagioclase, 55.2; olivine, 15.8; diopsidic augite, 10.1; interstitial ore-charged glass, 18.9. Some of the larger plagioclase laths are normally zoned from An_{62} in the cores to An_{54} at the margins; the smaller, unzoned laths consist of sodic labradorite. The gray-green augite is partly intergranular and partly in subophitic relation to the feldspar. One phenocryst has an extinction angle, Z to c, of 42° and an optic angle of 52°. Axial angles of other grains range from 48° to 58°. The olivines vary in size between 0.5 and 1.5 millimeters. Their optic sign is invariably negative, the angle ranging from 82° to 76° and suggesting a range in composition from Fo_{54} to Fo_{64}. A few crystals exhibit zoning from cores of Fo_{63} to rims of Fo_{55}. Many of the smaller olivines are fresh, but most of the larger ones are more or less altered to iddingsite, particularly in the cores. The rest of the lava consists of a brownish-black glass containing dusty titaniferous magnetite and thin plates of ilmenite.

The highly vesicular, spheroidally weathered basalts that form the bulk of Cerro Colorado differ from the above mainly in the more abundant development of iddingsite. In the larger olivines only the cores are altered; in the smaller ones alteration is usually lacking.

Hence the iddingsite appears to have been formed at an early stage by oxidation and hydration resulting from escape of volatiles from an iron-rich interstitial liquid. Edwards (1938) has noted elsewhere that it is especially in basalts with iron-rich glass that iddingsite develops; in chemically identical basalts in which the iron ores are completely crystallized he found the mineral to be absent. In the Parícutin region, this rule does not hold except among the basalts of Cerro Colorado. For instance, iddingsite is plentiful in holocrystalline lavas erupted by Cerro de Cutzato, Cerro Prieto, and Cerro de Cópitiro. What characterizes all these iddingsite-rich rocks is, not the presence of iron-rich glass, but the late crystallization of the abundant iron ores.

Other olivine basalts occur in the Zumpinito formation near Jucutacato. In these, olivine is the only porphyritic mineral, making up between 5 and 8 percent of the volume of typical specimens. Generally it is rimmed with either antigorite or bowlingite. The groundmass is a trachytoid felt of slender microliths of medium labradorite with intergranular specks of augite and ore. On Cerro de Las Ventanas, coarse-grained olivine-augite basalts are interbedded with tuffaceous clays; on Cerro de Charanda, there are holocrystalline basalts with the following percentages by volume: porphyritic olivine ($2V=80°$, negative), marginally altered to bowlingite, 5; calcic labradorite, 50; diopsidic augite, 30; and magnetite, 15.

INTRUSIVE ROCKS OF UNDETERMINED AGE

Discussion of the fragments of plutonic rock blown out of Parícutin is deferred to pages 258–259. Here attention is confined to the intrusive rocks found on the Bolita de La Magdalena, a short distance south of Uruapan.

Nothing is more characteristic of these rocks than their rapid variation both in texture and mineral composition. Three specimens are selected for brief description. In the first, phenocrysts of plagioclase (An_{65} to An_{75}), up to a centimeter in length, predominate. All are rendered turbid by clouds of irresolvable pinkish dust, possibly hematite. The other porphyritic constituent is olivine, partly altered to bowlingite and bordered by reaction rims of diopsidic augite. The groundmass is composed of a dense intergrowth of labradorite, hypersthene, augite, and iron ore with interstitial patches of quartz and orthoclase.

The second type is much finer grained and more nearly equigranular. Crystals of augite and hypersthene, commonly in parallel intergrowth, exhibit marked schillerization due to exsolution of hematite; they reach a length of 1 millimeter and constitute about 20 percent of the volume. Subhedral crystals of calcic labradorite make up 60 percent by volume; olivine, 3 percent; and ore, 4 percent. Interstitial quartz and orthoclase with accessory apatite constitute the remainder.

The third type, like the first, is marked by dust-filled laths of labradorite, some of which measure as much as 3 millimeters in length. These are much fractured and veined with clear, granular andesine. No porphyritic ferromagnesian minerals are present. Minute augite grains are enclosed by the feldspar phenocrysts, and, along with hypersthene, they are intergrown with anhedral grains of andesine in the dense, allotriomorphic groundmass. Unlike the other types, this one is devoid of late-crystallizing quartz and orthoclase. All three types are classed as gabbros.

ROCKS OF POST-ZUMPINITO AGE

GENERAL STATEMENT

The post-Zumpinito rocks of the Parícutin region show only a limited range in composition—from olivine basalts to olivine-free pyroxene andesites. Indeed, throughout the Neo-Volcanic Zone of Mexico, dacites and rhyolites are notably rare in comparison with those present among the older Tertiary volcanic rocks.

The present survey has shown, however, that in the Parícutin region andesites are more plentiful among the lavas of Pleistocene and Recent age than was previously supposed. It may well be that more detailed studies in other parts of the Neo-Volcanic Zone will show the same to be true there. Pale-gray, porphyritic and pilotaxitic pyroxene andesites are easy to recognize even in the field, but many dark, hyalopilitic and vitrophyric andesites are only to be distinguished by chemical analysis.

The naming of fine-grained and glass-rich lavas is a notoriously troublesome business. Usually, though not always, an abundance of porphyritic olivine denotes either a basalt or a basaltic andesite, but the distinction between basalt and andesite on the basis of the composition of the feldspar is unsatisfactory. Certainly the presence of labradorite is not to be regarded as diagnostic of basalt; if it were, then no lava in the Parícutin region would be classed as andesite despite the compositions revealed by analyses (table 1). There is such a wide range in the composition of the feldspar in most flows, not only within individual phenocrysts but between porphyritic and microlithic crystals, that it becomes virtually impossible to estimate an average composition. Besides, the composition of the interstitial glass and cryptocrystalline material is only approximately known.

Separation of basalt, basaltic andesite, and andesite must therefore be based on the bulk composition as revealed by chemical analysis. In the present report, lavas containing less than 54 percent silica, with negative *qz* values and without normative quartz, are classed as "basalts." Lacking chemical analyses, flows abnormally rich in olivine and in calcic labradorite or more calcic feldspar are also grouped as "basalts." Lavas with positive *qz* values of less than 20 (generally less than 10) and with modal olivine are named "basaltic andesites." Lavas with positive *qz* values of more than 20, but still carrying modal olivine, are referred to as "olivine andesites." Finally, lavas with more than 55 percent silica and with high positive *qz* values and devoid of olivine are termed "andesites."

OLIVINE-FREE ANDESITES

All the lavas of the oldest volcanoes of the region belong to this group—those of Cerros de Tancítaro, Cerros de San Marcos, Cerro del Aguila, and Cerros de Angahuan. Many flows of the next-oldest volcanoes, those of the Cerros de Los Hornos, belong to the same category. However, eruption of olivine-free andesites continued to a much later time, forming Mesa de Zirimóndiro and Mesa de Huanárucua and the most voluminous of all the recent flows of the Parícutin region—those of Cerros de Capacuaro. In the following notes the andesites are discussed in the order of their eruption insofar as that can be determined.

ANDESITES OF CERROS DE TANCITARO AND CERROS DE SAN MARCOS

The lavas of these volcanoes are coarsely porphyritic, pilotaxitic pyroxene andesites. Except for slight variations in texture and in the ratio of hypersthene to augite, and save for the presence in a few flows of a little oxyhornblende, they are remarkably uniform. None contains either biotite or quartz unless some of the latter is included in the cryptocrystalline groundmass. They resemble the principal lavas of such better-known Mexican volcanoes as Colima, Popocatépetl, Orizaba, and Nevado de Toluca, and they are similar to the pyroxene andesites of such coeval cones in the Cascade Range as Mounts Shasta, Rainier, Baker, and Hood.

The principal type is represented by the analyzed sample from Peña del Horno, illustrated in figure 87*A*. This has the following percentages by volume: (phenocrysts) plagioclase, 36; augite, 4; hypersthene, 6; (groundmass) granular ore, 8; augite, 6; microlithic feldspar, 38; oxyhornblende, 1; and cristobalite, 1.

The range in composition of the porphyritic feldspar is particularly striking. Even unzoned crystals vary in composition from An_{48} to An_{70}. Most of the phenocrysts are strongly zoned in an oscillatory fashion, the rims being notably more calcic than the cores. For example, one phenocryst has a core of An_{52} surrounded by shells

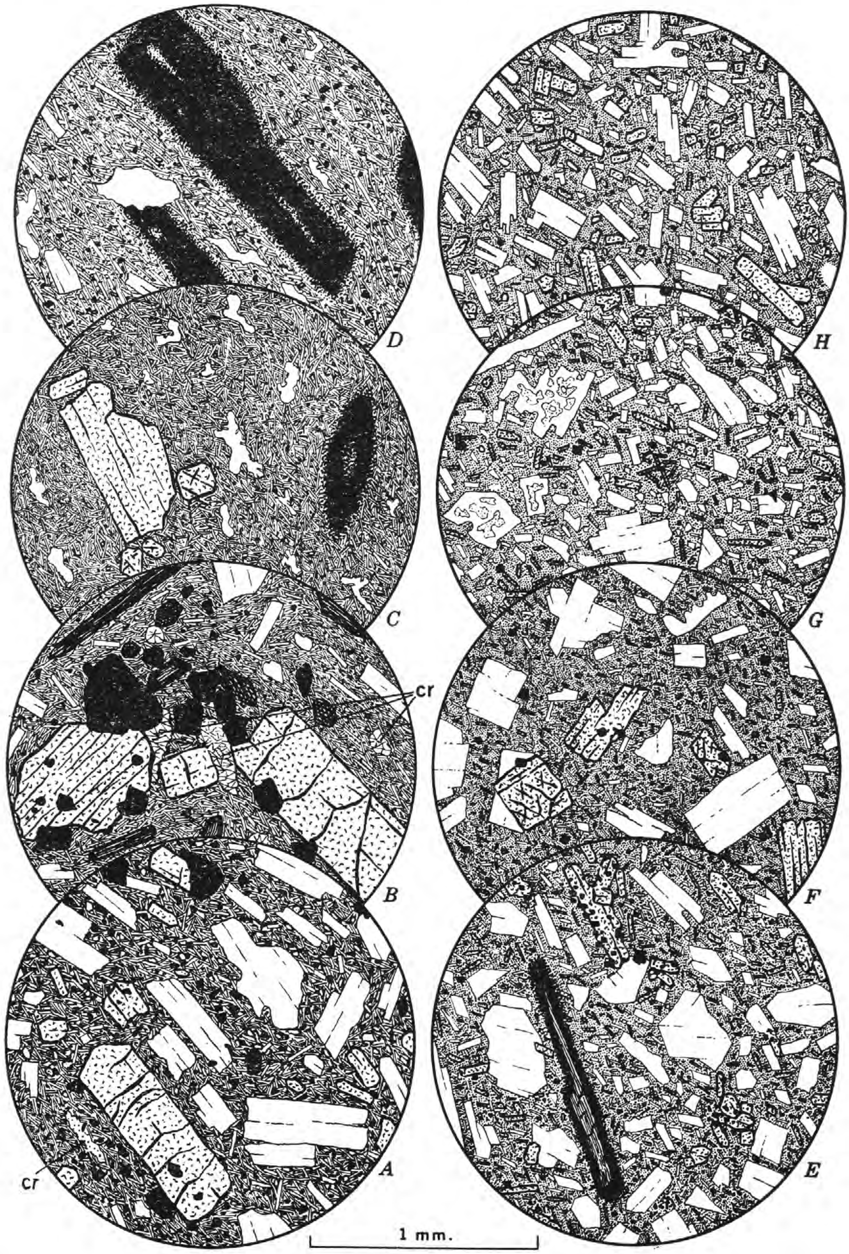


FIGURE 87.—Andesites from vicinity of Paricutin.

first of An_{48} and then of An_{62}, enclosed by a rim of An_{68}. An adjacent crystal shows an outward change from An_{47} through An_{57} and An_{50} to a rim of An_{56}. Along with the phenocrysts that show reverse zoning are others that exhibit normal oscillatory zoning. Many crystals of both types are spongily replaced by pale-yellow glass. These features denote a complex magmatic history. Elsewhere, Wenk (1945) has observed that oscillatory zoning of feldspar is especially well developed where hornblende also is present, and although that mineral is now rare among the lavas of Tancítaro, it may have been more plentiful prior to eruption and may have been almost completely resorbed during the rise of the lavas to the surface. This, however, cannot be the entire explanation of the many kinds of zoning. More likely much of the variation is to be ascribed to mingling of magmas before extrusion.

In contrast to the porphyritic feldspars, the microliths are relatively uniform, varying only between An_{49} and An_{54}. Precise determination of the cryptocrystalline matrix is impossible, but since the lava contains 1.43 percent K_2O, orthoclase is presumed to be an important constituent. Minute cracks and irregular pores are partly occupied by cristobalite and hematite, products of fumarolic vapors.

EXPLANATION OF FIGURE 87

A, Pilotaxitic hypersthene andesite (79). Peña del Horno. Hypersthene, augite, and calcic plagioclase phenocrysts in a matrix of granular ore, augite, and andesine-labradorite laths with interstitial cristobalite (Cr). Table 1, analysis 10.

B, Hornblende-bearing pyroxene andesite (111a). Near summit of Cerros de Tancítaro. Phenocrysts of oxyhornblende, hypersthene, augite, and labradorite in a matrix resembling that of the preceding lava. Table 1, analysis 17.

C. Augite-hornblende andesite (58). South edge of Mesa de Huanárucua, approximately 1 mile north of San Juan Parangaricutiro. Phenocrysts of augite and altered hornblende in a dense hyalopilitic matrix of plagioclase, granular ore, and augite with interstitial pale-buff glass. Table 1, analysis 14.

D, Hornblende andesite (113). East edge of Mesa de Zirimóndiro. Phenocrysts of oxyhornblende, largely replaced by magnetite, in base of plagioclase laths, granular ore, augite, and interstitial cryptofelsite. Table 1, analysis 6.

E, Pyroxene-hornblende andesite (91). Flow from Cerros de Capacuaro, between villages of Capacuaro and Arantepacua. Oxyhornblende, hypersthene, and labradorite phenocrysts in a glass-rich base carrying plagioclase, augite, and ore. Table 1, analysis 12.

F, Hypersthene andesite (90). Southeast slope of Cerro del Aguila. Phenocrysts of hypersthene and labradorite in a glass-rich base stippled with augite, ore, and laths of andesine. Table 1, analysis 16.

G, Pyroxene andesite (65). Near summit of Cerro de La Purísima. Microphenocrysts of augite and hypersthene, in about equal amount, and phenocrysts of labradorite in a glass-rich base carrying granular ore, augite, and microlithic plagioclase. Table 1, analysis 15.

H, Hypersthene andesite (14). Near summit of Cerro de La Cruz. Phenocrysts of labradorite and hypersthene in a glass-rich matrix carrying microliths of andesine and rare granules of augite and ore. Table 1, analysis 18.

Phenocrysts of augite rarely exceed 1 millimeter in length. They are pale yellowish green in color and are devoid of sensible pleochroism. One crystal has an optic angle of 55° and an extinction angle, *Z* to *c*, of 43°; another has an optic angle of 52° and an extinction angle of 40°, together with a birefringence of .038. These properties indicate the augite to be diopsidic.

Porphyritic hypersthene occurs in prisms of about the same dimensions as the augite. Optic angles denote molecular percentages of 32 to 33 $FeSiO_3$. Some prisms show marginal alteration to hematite as a result of oxidation.

Almost identical andesites are widespread along the summit ridge of Cerros de Tancítaro and on the upper, southern flank of the volcano. The flow forming Cerro de San Pedro, about a mile north of Peña del Horno, is noteworthy both for its high content of cristobalite and tridymite and for the intense pleochroism of its hypersthene, the optic angle of which indicates a molecular percentage of 38 $FeSiO_3$. Among the flows along the eastern base of the volcano are some in which hypersthene is ten times as plentiful as augite, and in several specimens both pyroxenes are almost completely replaced by magnetite and hematite.

True hornblende andesites have not been seen on Cerros de Tancítaro. Among the flows that carry up to 5 percent porphyritic hornblende are those on the ridge below Cerro de San Pedro, in the canyon of the Río del Barranco, and on the south side of the volcano about halfway down.

The analyzed specimen of hornblende-bearing pyroxene andesite is illustrated in figure 87*B*. It comes from the trail on the south side of the mountain. Approximately a third of the rock consists of oscillatory zoned crystals of plagioclase, ranging from An_{50} to An_{65} in composition and up to 6 millimeters in length. Prismatic hypersthenes, up to 2 millimeters long, are four times as common as augite; together they make up 10 percent of the volume. Oxyhornblende phenocrysts, largely replaced by ore and augite, measure up to 1 millimeter in length and constitute 3 percent of the volume. The pleochroism is as follows: X = pale yellow; Y and Z = deep reddish brown. The extinction angle, Z to c, varies up to 10°, and the optic angles range between 70° and 75°.

The fine groundmass consists of a pilotaxitic felt of andesine microliths and cryptocrystalline material stippled with specks of augite and ore and with slender needles of apatite. To judge from the chemical analysis (table 1, analysis 17), the interstitial material probably contains much orthoclase.

The andesites of the San Marcos volcanoes are essentially like those just discussed from Cerros de Tancítaro. A representative sample has already been illustrated by Schmitter (1945).

ANDESITES OF CERRO DEL AGUILA

Chemical analysis (table 1, analysis 16) reveals that the lavas of this volcano resemble the principal type on Cerros de Tancítaro, and the microscope shows that they are also hypersthene-augite andesites. Their field appearance, however, is quite different. The lavas of Tancítaro and San Marcos are typically pale-gray, pilotaxitic flows devoid of conspicuous vesicles; the flows of Cerro del Aguila, on the other hand, are black, highly vesicular and glass-rich andesites only to be distinguished from the basalts of adjacent cones by the absence of olivine. Except that they are much richer in porphyritic feldspar, they more nearly resemble the coeval andesites of the Angahuan volcanoes and the much younger andesites of the Capacuaro cone. In brief, they are classed as vitrophyric pyroxene andesites.

Despite their wide extent they show little variation. It is enough, therefore, to describe the analyzed specimen illustrated in figure 87*E*. This has the following percentages by volume: plagioclase, 44; hypersthene, 8; augite, 4; ore, 4; interstitial glass with microliths of feldspar and augite, 40.

The glass is of a clear, warm-brown color. Its refractive index, 1.524 ± .002, suggests a silica percentage of approximately 62 (George, 1924). The plagioclase phenocrysts range in length up to 2 millimeters, the larger ones showing normal zoning from sodic bytownite to medium labradorite, while the smaller ones consist of medium to sodic labradorite. Hypersthene forms euhedral and subhedral prisms, mostly less than 0.25 millimeter long but occasionally up to 1 millimeter in length. Measurements on the universal stage reveal a wide range in composition. One unzoned prism has an optic angle of 68° (= 34 percent $FeSiO_3$); one zoned crystal has a core with 14 percent $FeSiO_3$ and a rim with 24 percent. Augite occurs in minute anhedral specks too small for accurate optical reading.

ANDESITES OF CERROS DE ANGAHUAN

The flows composing the twin volcanoes of Angahuan vary from black, aphyric, glassy types that break with a splintery or conchoidal fracture to more abundant varieties that carry phenocrysts of augite and feldspar large enough to be seen by the unaided eye. None, however, are as strongly porphyritic as the andesites of El Aguila.

Characteristic of the glass-rich flows are those of the western flank of the northern cone. These are hyalopilitic lavas in which brown glass with indices of about 1.53 (= 60 percent SiO_2), stippled with specks of augite and ore, makes up about half the volume. Microphenocrysts of augite ($2V = 60°$; Z to $c = 42°$), mostly between 0.1

and 0.3 millimeter across, constitute no more than 2 percent by volume. The rest is made up of fluidally arranged microliths of sodic labradorite.

Typical of the vitrophyric flows are those seen along the margins of the summit plateau of the northern volcano, such as the one analyzed (table 1, analysis 15) and illustrated (fig. 87*G*). About 40 percent of the volume of this specimen is composed of brown glass dotted with euhedral grains of magnetite and anhedral specks of augite. Refractive indices of 1.519 to 1.523 ± 0.002 suggest that the glass has a silica percentage of approximately 63. Fifteen percent of the lava consists of phenocrysts of plagioclase up to 1 millimeter long. Almost all these phenocrysts are riddled with blebs and stringers of pale-buff glass, and some are almost completely vitreous. While most plagioclase phenocrysts show normal zoning from cores of sodic bytownite to rims of medium labradorite, many, particularly those that show interior vitrifaction, are marked by reverse zoning within the same range of composition. Perhaps the latter are xenocrysts derived by commingling of magmas prior to extrusion. Approximately a third of the specimen is made up of microliths of calcic andesine. The remaining 10 percent is comprised in equal amounts of diopsidic augite ($2V = 55°$ to $60°$; Z to $c = 43°$) and hypersthene ($2V = 75°$ to $80°$) in grains up to 1 millimeter in length.

ANDESITES OF CERROS DE LOS HORNOS AND CERROS DE PARACHO

The multiple cones of Cerros de Los Hornos are composed in part of olivine-bearing basaltic andesites but mainly of olivine-free, hyalopilitic and vitrophyric andesites. On the north and east flanks of the cluster, flows of vitrophyric hypersthene andesite predominate. Half of a representative sample consists of laths of calcic to medium labradorite between 0.1 and 0.5 millimeter in length. Hypersthene, the only porphyritic constituent, makes up 7 percent of the volume, occurring in stumpy prisms up to 0.5 millimeter long and as slender needles of much smaller dimensions. The latter contain from 22 to 26 percent $FeSiO_3$ and are distinctly more pleochroic than the phenocrysts, the optic angles of which denote molecular percentages of 14 to 18 $FeSiO_3$. The remaining 40 percent of the andesite is made up of dark-brown glass, with a refractive index of 1.520 ± .002 (= 63 percent SiO_2), stippled with ore and augite and sporadic needles of apatite.

On the south and southwest sides of the cone cluster, similar andesites again predominate, but some carry more and larger phenocrysts of labradorite and in them the hypersthene is accompanied by sparse phenocrysts of diopsidic augite.

On Cerros de Paracho a comparable association of olivine-bearing basaltic andesites and olivine-free hypersthene andesites is to be seen.

The latter resemble those from the Cerros de Los Hornos already described.

HORNBLENDE ANDESITE OF MESA DE ZIRIMONDIRO

The only hornblende andesites in the Parícutin region are those forming Mesa de Zirimóndiro, close to Tancítaro village. The analyzed specimen (table 1, analysis 6), which is depicted in figure 87*D*, is typical of the gray, unoxidized, microvesicular lava making up the greater part of the flow. Phenocrysts of oxyhornblende, between 0.5 millimeter and 2 millimeters in length, constitute 8 percent of the volume, though in other specimens the mineral is twice as abundant. Most of the hornblende is replaced by a dense intergrowth of magnetite, augite, and yellow glass; where relics are preserved, the pleochroism is from X = pale yellow to Y and Z = deep russet. Extinction angles, Z to c, range up to 5°. The only other porphyritic constituent is feldspar, which is normally zoned from calcic to medium labradorite. It makes up 2 percent of the volume. Approximately two-thirds of the volume consists of slender laths of sodic labradorite, between 0.1 to 0.2 millimeter long, in subparallel arrangement. Minute grains of augite ($2V = 55°$; Z to $c = 44°$) total 5 percent, the remainder being composed of interstitial glass and cryptocrystalline material stippled with dusty ore and sporadic spheroids of cristobalite.

Where the andesite of Zirimóndiro has been oxidized by fumarolic vapors, cristobalite is more plentiful and finely divided hematite is scattered throughout the matrix. In these rocks the oxyhornblende phenocrysts are almost completely converted to hematite and limonite, and the augite, which is pale green in the unoxidized lava, has a faint brownish tint and lower birefringence.

Chemical analysis (table 1, analysis 6) shows the andesite of Mesa de Zirimóndiro to be less siliceous than most of the olivine-bearing basaltic andesites of the region.

AUGITE ANDESITE OF MESA DE HUANARUCUA

The thick flow forming Mesa de Huanárucua is a fine-grained, microvesicular andesite in which the only phenocrysts are sporadic crystals of diopsidic augite. Where oxidized by residual vapors, the lava is pale pink; elsewhere it is light gray.

The analyzed specimen of pink lava (table 1, analysis 14) is shown in figure 87*C*. Phenocrysts of diopsidic augite ($2V = 55°$; Z to $c = 43°$), up to 1 millimeter long, constitute 3 percent of the volume. Occasional clusters of granular magnetite with forms suggestive of derivation by break-down of hornblende make up 1 percent. The dense groundmass has the following percentages by volume: microlithic plagioclase (Ab_1An_1), 65; granular augite, 10; interstitial glass, 13; grains of ore and flakes of hematite, 8.

Except for the lack of hematite, the gray unoxidized lava is not essentially different, although in one sample a few prisms of hypersthene accompany the augite.

VITROPHYRIC ANDESITE OF CERROS DE CAPACUARO

The voluminous lavas recently erupted by the Capacuaro cone are dark-gray to black, glass-rich andesites with a sugary, diktytaxitic texture. Save for minor variations in the proportions of the constituents, none of the specimens examined differs from the one analyzed (table 1, analysis 12) and illustrated (fig. 87*E*). This has the following percentages by volume: plagioclase, 55; hypersthene, 5; augite, 15; oxyhornblende, 1; ores and apatite, 4; interstitial glass, 20.

Most of the plagioclase laths measure between 0.2 and 0.3 millimeter in length; they consist of unzoned sodic labradorite. The larger feldspars, some of which reach a length of 1 millimeter, show normal oscillatory zoning, and the cores of some are spongily replaced by glass. One zoned phenocryst has a nucleus of An_{76} enclosed by a thin shell of An_{65}; others show zoning within smaller limits.

The hypersthene occurs as stumpy euhedral prisms up to 1 millimeter in maximum dimension. Its pleochroism is distinct, and the optic angle indicates a molecular percentage of 26 $FeSiO_3$. A few crystals of augite reach the same size, but mostly the mineral is in anhedral grains less than a quarter as large. One of the larger augite grains has an optic angle of 52° and an extinction angle, Z to c, of 42°; another has an optic angle of 58° and an extinction angle of 44°. Sporadic phenocrysts of oxyhornblende show marginal alteration to iron ore. Their cores are pleochroic from pale yellow to deep brown; they show straight extinction and have optic angles of 70° to 75°. Finally, the interstitial glass varies in color from pale to dark brown and in refractive index from 1.518 to 1.522 ± .002, suggesting a silica percentage of about 63.

OLIVINE-BEARING ANDESITES: LAVAS OF CERRO DE SURUNDARO

The youthful lavas of Cerro de Surúndaro are extremely uniform both in texture and mineral composition. All are dark-gray to black, vesicular flows liberally spotted with phenocrysts of olivine but only sparsely relieved by porphyritic feldspar. In the field they are readily mistaken for olivine basalts; however, chemical analysis (table 1, analysis 13) shows that they are andesites with a positive *qz* value of 25.

The analyzed specimen is depicted in figure 88*H*. Phenocrysts make up 14.8 percent by volume, as follows: olivine, 4.3; hypersthene, 0.4;

plagioclase, 10.1. All the olivine is fresh; optic angles suggest a range in composition between Fo_{67} and Fo_{76}. Most of the hypersthenes have optic angles of 70° ± 2°, but some show reverse zoning, cores with an optic angle of 64° (= 40 percent $FeSiO_3$) being surrounded by narrow rims with an angle of 82° (= 20 percent $FeSiO_3$). For the most part, the porphyritic feldspar is medium labradorite (An_{60-62}), but a few crystals exhibit normal zoning from An_{60} to rims of An_{55}.

The groundmass of the lava is comprised of the following percentages by volume: microliths of calcic andesine, 24; euhedral prisms of augite, 30; euhedral hypersthene, 5; magnetite, 6; apatite, 1; and clear brown glass with an index of 1.530 ± .002 (=60 percent SiO_2), 35 percent.

Some specimens of andesite from Cerro de Surúndaro differ from the foregoing in containing as much as 8 percent by volume of porphyritic olivine; in such rocks the amount of hypersthene is correspondingly reduced.

OLIVINE-BEARING BASALTIC ANDESITES

Among the younger lavas of the Parícutin region, those belonging to the group of olivine-bearing basaltic andesites are probably the most abundant. It should be repeated, however, that it is impossible to distinguish them in the field either from olivine-bearing andesites or from true olivine basalts; even with the aid of the microscope the distinction may be impossible.

CERROS DE LOS HORNOS AND CERROS DE PARACHO

Reference has already been made (p. 240) to the fact that the lavas of these volcanoes are partly olivine-free andesites and partly olivine-bearing basaltic andesites. On Cerros de Los Hornos the latter are found chiefly on the southeast flank. They are black, aphyric flows carrying approximately 4 percent by volume of olivine crystals, up to 0.1 millimeter across, many of which are marginally altered to antigorite. Equally small grains of augite and hypersthene together constitute 9 percent of the volume. Between 60 and 65 percent consists of slender microliths of medium labradorite, and 4 percent is composed of granular ore. The remainder is brown glass with a refractive index of 1.530 ± .002 (= 60 percent SiO_2).

Similar flows are widespread on Cerros de Paracho. With them are others that carry up to 10 percent by volume of olivine and contain abundant glass with indices approximating 1.550 (= 54 percent SiO_2). Such are the lavas exposed half a mile southeast of the village of Paracho. Still other flows, including those near the village of Aranza, are equally rich in olivine but are holocrystalline. Probably chemical analyses would reveal these to be true basalts rather than basaltic andesites.

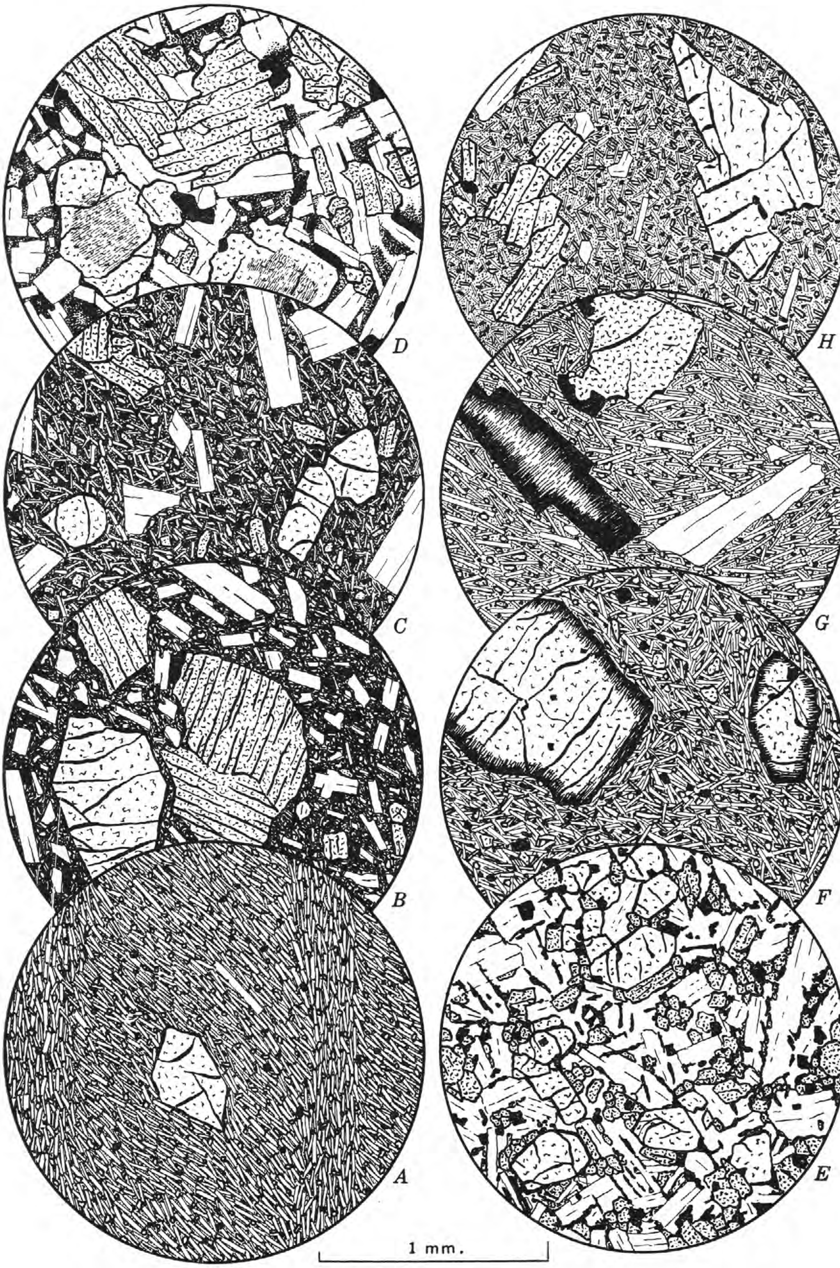


FIGURE 88.—Basalts and basaltic andesites from vicinity of Paricutin.

TZARARACUA FLOW

The lava discharged from the foot of Cerro de Jicalán into the valley of the Río de Cupatitzio to form Cascada de Tzaráracua is a dense, pale-gray basaltic andesite in which a few crystals of plagioclase and olivine are the only constituents discernible by means of the hand lens.

The analyzed sample (table 1, analysis 11) is illustrated in figure 88*A*. It comes from the upper part of the flow where it is crossed by the trail leading to the base of the falls. Phenocrysts make up only 5 percent of the volume, as follows: calcic labradorite, up to 1 millimeter long, 1 percent; diopsidic augite, up to 0.5 millimeter across, with an optic angle of 58° and an extinction angle, *Z* to *c*, of 43°, 1 percent; and olivine, up to 1 millimeter across, 3 percent. Optic angles of the olivine vary from 85° (negative) to 90°, and some of the crystals are altered marginally to hematite and bowlingite. The rest of the lava is a dense fluidal felt, percentages by volume of which are: microlithic calcic andesine, 63; augite, 16; hypersthene, 6; ore, 4; apatite, 1; and cristobalite, 1; with interstitial yellowish glass flecked with hematite, 4.

The most arresting feature of the lava is the evidence of shearing produced during the final stages of movement. Within adjacent lenses,

---

EXPLANATION OF FIGURE 88

A, Olivine-bearing basaltic andesite (38). Cascada de Tzaráracua. Olivine phenocrysts set in a fluidal, intergranular matrix of plagioclase, augite, and ore, showing the effects of shearing prior to solidification. Table 1, analysis 11.

B. Olivine-augite basaltic andesite (35). Lava mound near east base of Cerro del Aire. Large phenocrysts of olivine and augite set in a glass-rich base stippled with plagioclase, augite, and ore. Table 1, analysis 5.

C, Olivine-augite basalt (63). Flow from Cerro de Tzintzungo, approximately 1 mile east of San Juan Parangaricutiro. Phenocrysts of olivine, augite, and calcic labradorite in a glass-rich base charged with granular ore, augite, and microlithic plagioclase. Table 1, analysis 4.

D, Coarse-grained olivine-augite basalt (45). Near summit of Cerro Colorado. Phenocrysts of olivine, with cores of iddingsite, and augite, with labradorite and titaniferous ore and black, iron-rich interstitial glass. Table 1, analysis 3.

E, Olivine-augite basalt (95). Recent flow from Cerro de Capatacutiro, on main highway approximately 4 miles northwest of Capacuaro. Holocrystalline lava composed of olivine, augite, labradorite, and granular ore. Table 1, analysis 1.

F, Olivine-rich basaltic andesite (10). Flow from Cerro de Cutzato, 3 miles southeast of San Juan Parangaricutiro. Phenocrysts of marginally serpentinized olivine in a dense holocrystalline matrix of labradorite laths, granular ore, augite, and rare hypersthene. Table 1, analysis 7.

G, Olivine-bearing basaltic andesite (121). South slope of Cerro Prieto. Phenocrysts of olivine, marginally altered to hematite and magnetite, and of calcic labradorite in a holocrystalline matrix of plagioclase, augite, and ore. Table 1, analysis 8.

H, Olivine-bearing andesite (92). Cerro de Surúndaro, near San Lorenzo. Phenocrysts of olivine and hypersthene in a glass-rich base studded with granular ore, prismatic augite, and plagioclase laths. Table 1, analysis 13.

0.3 to 0.5 millimeter thick and up to 2 or 3 centimeters long, the orientation of the feldspar laths differs markedly, so that the texture resembles cross bedding on a minute scale. Seen in the field, one set of laminae is almost horizontal, lying parallel to the lava surface, while the other is inclined at angles up to 40°. Nowhere do the laminae cross each other as bands of microliths often do in obsidians that have moved by shearing (Philipp, 1936), nor is there any difference in the mineral content of the laminae as there is in certain sheared basalts described from Vesuvius. Between 150 and 200 feet below the top of the flow the sheared texture disappears; at lower levels the fluidal banding is much less distinct and in general horizontal.

A specimen from the base of the flow at the foot of the falls is typical of the quickly chilled bottom. Aside from the absence of shearing effects, it differs from the foregoing chiefly in the much larger proportion of interstitial glass, the refractive index of which suggests a silica percentage of between 62 and 63.

CERRO DEL AIRE AND CERRO DE COPITIRO

The long flows discharged by the triple cone of Cerro del Aire and adjacent vents are characterized by abundant phenocrysts of plagioclase, augite, and olivine in a dark, vesicular matrix. The sample selected for analysis (table 1, analysis 5) and illustration (fig. 88*B*) comes from the lava mound built over the vent a short distance east of the triple cone. In composition it lies close to the border line between basalt and basaltic andesite, having a *qz* value of 3. Probably other flows from the same source are true basalts.

The analyzed lava is an intersertal olivine-augite basaltic andesite unusually rich in phenocrysts. Together these make up 42 percent of the volume (olivine, 6; augite, 6; feldspar, 30). Most of the olivines measure between 0.25 and 0.3 millimeter, though a few reach 1 millimeter in length. All are fresh. Three zoned crystals have optic angles suggesting cores of pure forsterite and rims of Fo_{72}. One phenocryst has a core of Fo_{67} surrounded by a narrow rim of Fo_{50}. No other lava in the region has been found to exhibit such a wide variation in the composition of its olivine.

The pale-green phenocrysts of diopsidic augite are stumpy subhedral prisms, commonly twinned on 100, of approximately the same dimensions as the olivine. Optic angles range from 47° to 53°, with corresponding extinction angles of 41° to 43°.

The feldspar phenocrysts are of the same dimensions. Unzoned phenocrysts vary from An_{72} to An_{78}; some of the larger crystals show normal, nonoscillatory zoning from An_{75} to An_{60}.

The groundmass has the following percentages by volume: microlithic labradorite (An_{52-55}), 22; augite, 19; ore, 8; apatite, 1; and brownish-black glass, 8.

A bomb collected from the peak where the three craters of Cerro del Aire join differs from the lava just described in the absence of porphyritic feldspar and augite. It is a scoriaceous rock, fully two-thirds of which is composed of black glass dotted with specks of augite, minute needles of plagioclase, and sporadic grains of hypersthene. Scattered throughout the matrix are slender laths of An_{65-68} and sparse phenocrysts of olivine ($2V = 90°$).

The lavas that extend southward from Cerro del Aire at least as far as Cheringerán are too much like the analyzed specimen to call for special description. Resting on them is a thick flow erupted from the foot of Cópitiro. This differs radically in texture, being a coarse, intergranular lava entirely devoid of glass. Phenocrysts of olivine total between 8 and 10 percent by volume; many show peripheral change to antigorite and hematite. Plagioclase ranges in length up to 0.5 millimeter, the composition departing little from An_{70}. It makes up approximately 55 percent of the volume. Green granules of augite, rarely more than 0.1 millimeter across, account for another 25 percent, the remainder consisting of granules of ore and a little apatite. Perhaps chemical analysis would reveal this lava to be basaltic rather than andesitic.

LAVAS OF CERRO DE PARIO AND CERRO DE LA ALBERCA

The flows composing Cerro de Pario and Cerro de La Alberca are notably uniform, and, except for a smaller content of phenocrysts, they are hardly to be distinguished from those of Cerro del Aire. In brief, they are hyalopilitic olivine-augite basaltic andesites either lacking in hypersthene or carrying no more than a few minute prisms of that mineral.

A representative specimen, collected in the saddle northeast of the top of Cerro de Pario, carries the following phenocrysts: olivine, up to 4 millimeters long, with $2V$ of 90°, 3 percent by volume; augite, up to 1 millimeter long, with $2V$ of 55° and extinction angle of 42°, 4 percent; plagioclase showing normal oscillatory zoning from sodic bytownite to medium labradorite in laths up to 1 millimeter long, 10 percent. The dense groundmass is made up of fluidally arranged microliths of sodic labradorite and granules of augite and ore embedded in dark-brown glass.

LAVAS OF CERRO DE CURITZERAN, CERRO DEL ANILLO, AND CERRO DE SICUIN

The dark, vesicular flows erupted by Curitzerán and its parasitic cones are marked especially by their low content of phenocrysts, particularly of olivine, and by their richness in glass. Seldom does olivine make up more than 2 percent of the volume or exceed 1 millimeter in length. Slender laths of sodic to medium labradorite constitute

60 to 65 percent by volume, few measuring more than 0.3 millimeter in maximum dimension. Exceptionally, augite forms phenocrysts up to 1 millimeter across, almost all of it occurring as minute anhedral specks between the laths of feldspar. In amount it varies between 12 and 15 percent. Minute prisms of hypersthene are invariably present, but they form only 2 or 3 percent of the volume. The remaining 20 to 30 percent of the lava consists of interstitial glass, the color of which changes from brown to black as the included grains of magnetite diminish in size. The refractive index of the clearest glass varies from 1.539 to 1.543 ± .002, suggesting a silica percentage of approximately 56.

LAVAS OF CERRO DE PARASTACO, CERRO DE MATANCERO, AND CERRO DE APUPAN

The flows belonging to the Cerro de Parástaco group of cones and to those between Cerros de Angahuan and Cerro de Surúndaro, of which Cerro de Matáncero and Cerro de Apupan are the two largest, closely resemble those of Cerro de Pario and Cerro de La Alberca, already described. In other words, their characters are intermediate between those of the lavas of Cerro del Aire and Cerro de Curitzerán.

LAVAS OF CERRO DE CUTZATO

The thick flows erupted by Cutzato are dense basaltic andesites, pale gray where fresh but changing to pink where oxidized by fumarolic vapors. They are totally devoid of porphyritic feldspar and augite, the only mineral recognizable by the naked eye being olivine, crystals of which average 1 millimeter across and occasionally reach a length of 3 millimeters. In the fresh lava the mineral is pale green; in the oxidized varieties it is iridescent and deep red in color.

The analyzed specimen (table 1, analysis 7) is shown in figure 88*F*. It typifies the pink variety. The percentages by volume are as follows: olivine, 6; slender laths of An_{70-80}, up to 0.2 millimeters long, 60; subhedral prisms of augite up to 0.15 millimeter long, 18; hypersthene, 3; magnetite and hematite, 5; interstitial cryptocrystalline material rich in acicular apatite, 8.

Of particular interest is the alteration of the olivine. The cores are fresh and have optic angles suggesting compositions between Fo_{86} and Fo_{88}. In some crystals the fresh nuclei are enclosed by sharply defined, narrow rims that show pleochroism in greens and an optic angle of 50° (positive). In other crystals the fresh cores grade into the colored fringes, the optic angle changing outward from 89° (negative) to less than 32° (positive), the position of the optic plane remaining constant. Concurrently the birefringence diminishes from 0.035 to 0.020. In still other crystals the rims are composed of magnetite and hematite. Apparently one is dealing here with early stages in the conversion of olivine to serpentine as a result of oxidation and hydration. Comparable changes have been described by Foslie (1931), who suggests that H_2 replaces the base metals of the olivine with preference for iron, which is liberated to form the marginal magnetite and hematite.

The gray facies of the lava of Cerro de Cutzato differs from the foregoing in the freshness of its olivine, the paucity of hematite, and the presence of a considerable amount of interstitial glass. Olivine makes up approximately 5 percent by volume; microporphyritic augite ($2V = 58°$; Z to $c = 43°$), about 1 percent; granular ore, 5 percent; microliths of calcic labradorite, 59 percent; interstitial glass with apatite needles, 15 percent. The refractive index of the glass is notably low (1.508 ± 0.002), indicating a silica percentage of about 65.

LAVAS OF CERRO PRIETO

Since only two samples from this volcano were studied microscopically and only one was analyzed chemically, it may be that there is more variety than appears from the general similarity of the flows as seen in the field.

The analyzed specimen (table 1, analysis 8), shown in figure 88*G*, is an intergranular basaltic andesite lightly sprinkled with phenocrysts of olivine, augite, and feldspar. The olivine, which constitutes 4.6 percent by volume, shows effects of oxidation and hydration like those seen in the lavas of Cerro de Cutzato. Some of the smaller grains are wholly replaced by magnetite and hematite, and most of the larger ones show a marginal development of these minerals. In other crystals a fringe of hematite passes inward to a zone of pale-green antigorite, and this in turn merges into a shell of hydrated olivine of low birefringence which envelops the fresh core.

Diopsidic augite occurs in anhedral phenocrysts up to 0.25 millimeter across with optic angles of $56° \pm 3°$ and an extinction angle of 44°. It makes up 2.5 percent of the volume. Porphyritic plagioclase (An_{70-75}), in laths up to 0.5 millimeter long, accounts for 2 percent. The remainder is a trachytoid felt of medium labradorite microliths with minute prisms of augite, granules of ore, and a little tridymite.

LAST OF THE FLOWS FROM CERROS DEL JABALI

The final flow from the Cerros del Jabalí vents was discharged probably within the last century. A sample from its snout near Los Conejos is shown by analysis (table 1, analysis 9) to be a basaltic andesite with a positive *qz* value of 7. As figure 89*B* indicates, it is decidedly rich in porphyritic feldspar but devoid of porphyritic augite. Plagioclase phenocrysts, showing normal zoning from cores of An_{65-67} to rims of An_{60}, make up 9.1 percent of the volume. Phenocrysts of olivine, which also range between 0.2 and 1 millimeter in length, make up 7.1 percent. These vary in composition between pure forsterite and Fo_{86}. The groundmass has the following percentages by volume: medium to sodic labradorite laths, 50.3; brownish-black glass, 23.1; ore, 4.6; and granular augite, 3.8. Hypersthene was not observed in this or any other of the Jabalí flows.

BASALTIC ANDESITES AND ANDESITES NEAR PARICUTIN

Probably all the lavas in the region between Parícutin and Cerro Prieto on the south and Cerro de Pario on the east are basaltic andesites. They are dark, vesicular, hyalopilitic flows stippled with phenocrysts of olivine, augite, and labradorite. In none of them does the content of hypersthene exceed 2 percent. Their resemblance to the lavas of Curitzerán makes it needless to give a special description of them.

The thick lavas forming the Equijuata-Capatzin ridge vary in texture from almost holocrystalline to hyalopilitic, the content of glass in some specimens rising as high as 20 percent. Phenocrysts of olivine usually make up about 5 percent of the rocks, but porphyritic feldspar and augite are either absent or present only in quite minor amount.

A specimen of glass-poor lava from the north slope of Cerro de Equijuata has the following percentages by volume: olivine, up to 1 millimeter across, slightly serpentinized, 5; laths of medium labradorite, rarely more than 0.5 millimeters long, 67; augite granules, 15; hypersthene, partly as reaction rims around olivine and partly as discrete grains, 3; ore, 8; interstitial glass, 2.

In a typical specimen of hyalopilitic lava from the Cerro de Capatzin ridge, the proportions of the constituent minerals remain approximately the same, but glass makes up between 15 and 20 percent. Its refractive index of 1.530 ± .002 suggests a silica percentage of 59. Unfortunately, microscopic study does not rule out the possibility that some of the flows forming the Equijata-Capatzin ridge are basalts rather than basaltic andesites.

In the region immediately to the south and west of the new volcano, the heavy mantle of ash from Parícutin has obscured all but a few exposures of the earlier lavas. This is much to be regretted, since the available specimens show a greater variety of lavas than elsewhere in the region studied. Along with the usual olivine-augite basaltic andesites there are olivine-poor, hypersthene-rich lavas which chemical analyses would probably reveal to be true andesites.

Among the latter are some of the flows near the southern margin of the Parícutin lava field, halfway between the Cocjarao triangulation station and the Nuréndiro spring, the source of which was either the cone of Cerro de Camiro or a fissure to the west. The phenocrysts of a typical sample had the following percentages by volume: olivine, 1; augite, 5; hypersthene, 3; magnetite pseudomorphs after oxyhornblende, 1; and normally zoned sodic bytownite-calcic labradorite, 5. The groundmass is composed of laths of medium labradorite, specks of augite and ore, and a minute amount of interstitial glass.

Closely associated with this supposed andesite, and perhaps representing the basal portion of the same flow, is a specimen containing four times as much porphyritic olivine but only rare phenocrysts of hypersthene and devoid of large augites and feldspar crystals. By comparison with lavas already described, this is classed as a basaltic andesite.

Another olivine-poor flow occurs near the southern base of Cerro de Canicjuata. Its phenocrysts are present in the following percentages by volume: olivine, 2; hypersthene, 5; diopsidic augite, 2; and calcic labradorite, 5. Laths of sodic labradorite in the groundmass make up approximately 55 percent of the volume; granules of augite, 10 percent; and brownish-black glass, 21 percent. This may be a true andesite.

The thick flow forming Mesa de Cocjarao may also be andesitic. Two specimens were examined under the microscope. One is holocrystalline and the other vitrophyric. The former was collected 200 yards south of the Cocjarao triangulation station. Phenocrysts of olivine, hypersthene, and calcic labradorite in equal amounts total 9 percent of the volume. The groundmass consists of microlithic labradorite with intergranular specks of augite and ore. The glassy specimen from the same flow, 100 yards north of the triangulation station, carries the same phenocrysts in about the same amounts, but here brown glass makes up 30 percent of the volume. Its refractive index, 1.520 ± .002, suggests a silica percentage of 63.

OLIVINE BASALTS

To this group are assigned all lavas with a negative *qz* value and those devoid of normative quartz, together with those particularly rich in olivine and calcic plagioclase. Just how common true basalts are in the Parícutin region will not be known until many more chemical analyses are available. Meanwhile it should be repeated for emphasis that many lavas are too near the proposed border line between basalts and basaltic andesites for safe identification. Among these doubtful lavas some have already been noted; others include many of the later flows of the Cerros del Jabalí cones. In the notes that follow, first the analyzed lavas are described, then those classed as basalts solely on the basis of microscopic study.

LAVAS OF CERRO DE TZINTZUNGO

The lavas of Cerro de Tzintzungo are among the most porphyritic of the younger flows of the Parícutin region, and most of them are especially rich in porphyritic feldspar. The analyzed specimen (table 1, analysis 4) is illustrated in figure 88*C*. It is an intersertal olivine-augite basalt with a negative *qz* value of 6. Phenocrysts make up 22.5 percent of the volume. Of these, olivine (6 percent) occurs in crystals up to 2 millimeters in length. All are fresh and clear except for inclusions of magnetite and a little secondary hematite. They range in composition between Fo_{72} and Fo_{82}. The porphyritic augite (5.5 percent) is mostly between 0.5 and 1 millimeter in diameter although a few crystals reach a maximum dimension of 1.5 millimeters. Optic angles vary between 56° and 58°, with corresponding extinction angles, Z to c, of 43° and 45°. The feldspar phenocrysts are of about the same size. Some show normal zoning from core to rim; others show normal oscillatory zoning in the cores and normal nonoscillatory zoning in the outer parts. The limits of composition are An_{80} inside and An_{70} outside.

The groundmass comprises 77.5 percent of the volume. Microliths of An_{70-75} total 39 percent; granules of augite, 18 percent; whereas the remainder consists of brownish-black glass charged with magnetite.

Four other specimens of lava from Tzintzungo, collected near San Juan Parangaricutiro and Cuezeño, closely resemble the above, but one sample, collected a quarter of a mile east of the analyzed rock (see map, pl. 8), deserves brief notice on account of its unusual richness in olivine and its low content of porphyritic feldspar and augite. In this lava the olivines reach a length of 3 millimeters and make up 10 percent of the volume. Optic angles indicate that the composition varies only between Fo_{74} and Fo_{76}. Phenocrysts of diopsidic augite and sodic bytownite total only 3 percent. The groundmass is a dense felt of calcic labradorite laths, anhedral specks of augite and ore, and interstitial black glass.

PAHOEHOE LAVA OF CERRO DE CAPATACUTIRO

The basalt of Cerro de Capatacutiro is the least siliceous lava in the entire region. The analyzed specimen (table 1, analysis 1) is shown in figure 88*E*. It is a holocrystalline, intergranular olivine-augite basalt of unusually coarse texture despite the fact that it comes from just below the thin glassy crust of the flow. Apart from a few exceptionally large crystals of feldspar, the texture is seriate. Micrometric analysis shows the following percentages by volume: olivine, 7.2; diopsidic augite, 22.2; plagioclase, 59.2; ore and accessory apatite, 11.4. Of two unzoned phenocrysts of feldspar 5 millimeters long, one consists of An_{77} and the other of An_{72}. Even the nonporphyritic feldspars range up to 4 millimeters in length, most of the larger ones showing normal zoning from sodic bytownite to medium labradorite, whereas the smaller ones are all of the latter composition. Few olivine crystals exceed 1 millimeter in width; some exhibit marginal development of magnetite and hematite, but most are fresh. They vary from Fo_{76} to Fo_{81}. The augite is of approximately the same size as the olivine and occurs as anhedral granules between the feldspars; its optic angles range from 55° to 58°. Only a little magnetite is included in the ferromagnesian minerals; almost all of it formed late, along with thin plates of ilmenite, in the groundmass.

A vesicular, more quickly chilled sample from near the western edge of the main flow of Cerro de Capatacutiro differs from the preceding specimen in containing about 20 percent black, ore-charged glass. In this lava, porphyritic olivines up to 1 millimeter long make up 12 percent of the volume. The percentage of augite is reduced to 15, and except for sporadic microphenocrysts all of it is in the form of minute specks in the glassy matrix. Laths of medium to calcic labradorite make up the remainder.

BASALTS FROM THE CERROS DEL JABALI CONE CLUSTER

The field appearance of the flows from the Jabalí cones resembles that of the lavas of Parícutin volcano, but although they show little variation in hand specimens, chemical analyses show that some are basalts and others are basaltic andesites.

Among the basalts is the lava forming the great flow that descends to the Río de Cupatitzio south of Uruapan. A specimen taken on the road between Uruapan and Jicalán has been analyzed (table 1, analysis 2) and illustrated (fig. 89*A*). It is a black, vesicular, hyalopilitic basalt lacking porphyritic feldspar but rich in phenocrysts of olivine. Indeed, no other lava in the region contains a larger amount of olivine, for here it makes up no less than 14 percent of the volume, ranging in size between 0.2 and 1 millimeter. Optic angles suggest compositions of Fo_{86-88}. Few grains of augite measure as much as 1 millimeter long, and most are less than half this length. Their optic angles approximate 60°, and their extinction angles vary from 42° to 45°. They total 17.2 percent of the volume. In contrast to the lavas of Parícutin volcano, this one is devoid of hypersthene. Laths of unzoned calcic labradorite comprise 52.3 percent of the volume, the rest being composed of magnetite-charged glass with indices of 1.548 to 1.553 $\pm$ 0.002 (= approximately 54 percent SiO_2).

The last flow to issue from the vent at the eastern foot of the main Cerros del Jabalí cone differs so little from the above that it also may be classed as a basalt.

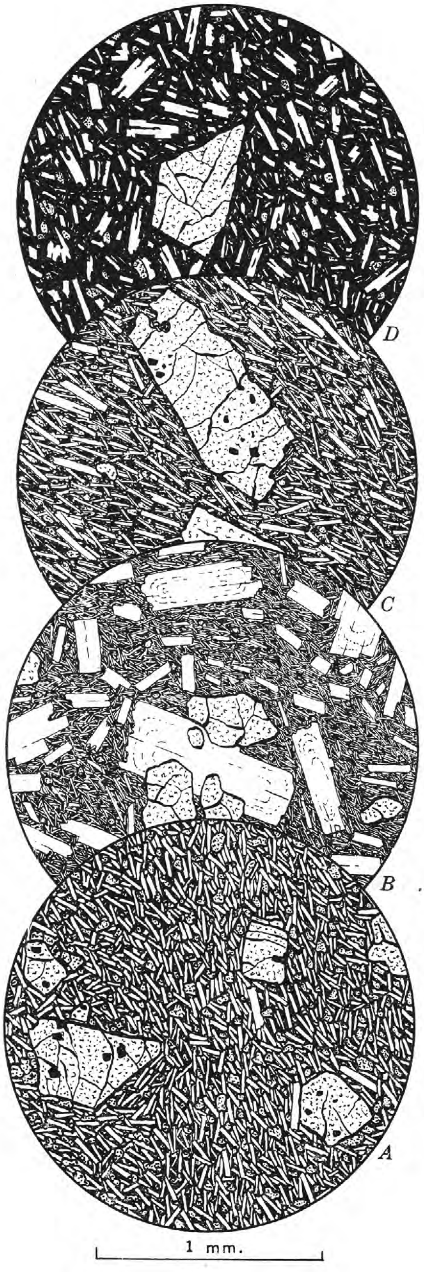


FIGURE 89.—Lavas from Cerros del Jabalí cones and Parícutin volcano. *A*, Olivine-rich hyalopolitic basalt (20). Main flow of Cerros del Jabalí cones, on highway between Uruapan and Jicalán. Phenocrysts of olivine in a dense base of labradorite laths, granular augite, ore, and dark brownish-black interstitial glass. Table 1, analysis 2. *B*, Olivine-bearing basaltic andesite (23). Latest flow of Cerros del Jabalí cones, approximately 1 mile east of Los Conejos. Labradorite and olivine phenocrysts in a glass-rich matrix carrying microlithic plagioclase, granular ore, and rare specks of augite. Table 1, analysis 9. *C*, Lava from Parícutin volcano, April 26, 1945, near Ahuán vent. Phenocrysts of olivine in a dense matrix of labradorite laths, hypersthene, and ore with a little augite and glass. *D*, Lava from Parícutin volcano, the flow that buried San Juan Parangaricutiro in July 1944. Glass-rich variety containing phenocrysts of olivine with microliths of plagioclase and hypersthene and rare grains of augite.

Reference is made, in conclusion, to the lava exposed along the paved highway where it makes a hairpin bend a short distance north of Uruapan. Its provenance is uncertain, but it is more likely an early flow from the Jabalí cones than a product of the older Alberca volcano. It is a holocrystalline lava containing 8 percent by volume of olivine crystals up to 3 millimeters across, with optic angles of 90° ± 2°, marginally altered to iddingsite, hematite, and magnetite. Fluidally arranged laths of calcic labradorite make up approximately half the rock and intergranular augite about a quarter, the remainder consisting of ore and a little apatite.

OTHER POSSIBLE BASALTS

Most of the flows discharged from fissures and cinder cones on the northwest flank of Cerros de Tancítaro are massive, pale-gray, vesicular lavas characterized by an abundance of large olivines, a great scarcity of porphyritic feldspar and augite, and an absence of hypersthene. Generally they are holocrystalline, and at most the content of glass amounts only to a few percent.

These flows spread down the valley of the Río de Itzícuaro from Tiripan via Zirosto and Barranca Seca beyond San Francisco; they include the long, thick flows erupted from the Cerros de Zirosto and those exposed on the canyon walls of the Río del Agua Blanca and other streams that descend toward Peribán. The trails linking Zirosto with Peribán and Apo reveal them in many places beneath a heavy cover of weathered ash.

Typical of these olivine-rich lavas are those that issued from Cerro de La Máscara, the largest cone of Cerros de Zirosto. A representative sample contains 10 percent by volume of olivine phenocrysts, up to 2 millimeters in length, marginally altered to iddingsite and hematite. Optic angles denote compositions between Fo_{94} and Fo_{98}. Phenocrysts of feldspar are completely lacking; slender laths of calcic labradorite, making up two-thirds of the volume, are restricted to a length of 0.3 millimeter. Anhedral grains of augite, rarely more than 0.1 millimeter across, occupy spaces between the feldspars. They total 15 percent of the volume. The remainder is made up of granules of magnetite with minor amounts of apatite and cristobalite.

With only trivial modifications, the above account applies to all the lavas on the lower, northwest flank of Cerros de Tancítaro, to those adjoining the road between Angahuan and Corupo, and to several of the flows far down the southern flank of Tancítaro, such as the one revealed on the walls of the Río del Fresno (p. 216).

Finally, it may be repeated for emphasis that some of the lavas of the Equijuata-Capatzin ridge and of the Cerro Prieto volcano are perhaps basalts rather than basaltic andesites.

864334—50——7

LAVAS OF PARICUTIN VOLCANO

Some of the flows and fragmental ejecta of the new volcano have already been described by Schmitter (1945) and Milton (1945). The salient features of these 1943 products do not differ materially from those displayed by later ones. Indeed, during the first 5 years of activity there has been singularly little variation in the mineralogical composition of the lavas from Parícutin volcano, the main differences being textural. No regular variation has been detected between successive flows or between the early and late flows of any particular vent. It must be admitted, however, that more detailed studies might reveal minor though significant differences related to changes in the nature of the pyroclastic ejecta. As far as the present studies go, all that can be said is that the fragmental ejecta and lavas contain the same minerals in approximately the same proportions but that the former usually contain more glass.

In the field all the flows from Parícutin volcano would be classed without hesitation as olivine basalts, and probably microscopic examination would not modify this designation. Yet chemical analyses (table 3) show that all but one of the lavas have positive qz values and contain normative quartz. (The exception has a qz value of zero.) Hence all are considered here as basaltic andesites. In a few flows small phenocrysts of plagioclase are present, as in the lavas of March 1943, but normally the only porphyritic constituent is olivine. This scarcity of porphyritic feldspar and the lack of pyroxene phenocrysts serve to distinguish the flows of Parícutin volcano from most of those erupted earlier in the immediate vicinity. Almost all the recent flows are rich in glass.

Two specimens have been selected for description and illustration (figs. 89*C*, 89*D*): one of the dominant glass-rich type and the other of the almost holocrystalline type. The first comes from the edge of the great flow that buried San Juan Parangaricutiro, on the outskirts of the town. Olivine makes up 5 percent of its volume. Most of the crystals measure about 0.5 millimeter across, but they range in size from almost irresolvable specks to phenocrysts 1.5 millimeters in maximum dimension. The larger ones vary in composition between Fo_{63} and Fo_{84}. A few are tabular parallel to the base, and many are deeply embayed by corrosion. The smaller olivines do not exhibit these features, being more or less spheroidal grains; their composition varies from Fo_{82} to Fo_{90}. In other words, though they crystallized later than the phenocrysts, they are more magnesian.

Next in order of abundance among the ferromagnesian minerals is hypersthene, which constitutes 4 percent of the volume. It occurs in subhedral prisms, mostly less than 0.05 millimeter long and rarely more than 0.1 millimeter in length. One of the larger prisms has an optic angle of 74°, indicating a content of 28 percent $FeSiO_3$. Rounded grains of augite total less than 1 percent of the whole; unfortunately they are too small for accurate optical reading.

Subparallel, slender laths of plagioclase, mostly between 0.1 and 0.2 millimeter long, comprise approximately half of the lava. The larger ones vary from An_{62} to An_{68}; the smaller ones range between An_{51} and An_{60}. Most of them are unzoned, but a few are normally zoned within the limits mentioned. Oscillatory zoning of the feldspars is notably rare, not only in this particular flow, but among all the lavas and fragmental ejecta of Parícutin. In this respect they differ from most of the older lavas of the vicinity.

The remaining 40 percent of this specimen is made up of brownish-black glass clouded with dusty ore. Satisfactory determinations of refractive index are not possible, but it is approximately 1.545 ± 0.005, suggesting a silica percentage of about 55.

The above description applies with trivial changes to most of the lavas erupted by Parícutin during the present study—that is, from November 1944 to May 1945. It applies also to specimens taken from the narrow dike which was exposed at the base of the main cone close to the Ahuán vent during the same period.

The second of the illustrated specimens (fig. 89*C*) comes from the Ahuán flow and was collected near the vent on April 26, 1945. This is as nearly holocrystalline as any of the lavas from the Parícutin volcano. Olivine again constitutes 5 percent of the volume, and again many of the larger crystals (Fo_{76-81}) show the effects of the solution The smaller olivines range in composition from Fo_{82} to Fo_{92} for the most part, but one has a core of Fo_{86} enclosed by a narrow rim of Fo_{72}. A few euhedral grains of ore are included in almost all of them. Subhedral to euhedral prisms of hypersthene total 10 percent of the volume; most measure less than 0.05 millimeter, and none exceeds 0.1 millimeter in length. Occasionally the mineral forms reaction rims around the olivines. Specks of augite of about the same size form approximately 1 percent of the whole. Slender laths of feldspar between 0.1 and 0.2 millimeter long, in subparallel arrangement, account for 70 percent of the volume, their composition varying from An_{60} to An_{65}. Granules and minute dendritic clusters of magnetite and ilmenite (?) total 7 percent; acicular apatite, less than 1 percent; whereas the remaining 5 percent is composed of dark-brown glass. Neither in this nor in any other flow from Parícutin volcano has orthoclase been detected. Presumably the potash revealed by analysis is largely contained in the interstitial glass.

In view of the fact that all other specimens studied, both lavas and bombs, are intermediate in character between the two varieties just discussed, particular mention seems to be unnecessary. The chief features of all, in comparison with the older flows of the neighborhood, are summarized as follows: a paucity of porphyritic feldspar; a scarcity of oscillatory zoning in the feldspars; a lack of porphyritic pyroxenes and scarcity of microgranular augite; a relative abundance of microlithic hypersthene; and the corrosion phenomena displayed by the olivine phenocrysts.

The chemical analyses listed in table 3 give further emphasis to the uniformity of the lavas from Parícutin volcano. Specimens taken from a single flow would probably show as much variation as do the analyzed lavas from different flows.

INCLUSIONS IN LAVAS AND BOMBS OF PARICUTIN

The first ejecta of the new volcano included blocks of basaltic andesite torn from the walls of the conduit close to the surface. Possibly some were derived from flows within the Zumpinito formation, but more probably they represent fragments of lavas of post-Zumpinito age like those exposed in the vicinity.

Accompanying these accidental pieces of andesite among the early ejecta were fragments of plutonic rock. At first these were abundant and large, many measuring several feet across. Later their number and size diminished. By 1945 it was rare to find plutonic chips more than a few inches across; by 1947 it required long search to find any at all. Moreover, during the early stages of activity many of the fragments were almost or quite unaltered; later it was exceptional to see fragments that were not largely altered to glass.

Concerning the partly vitrified xenoliths discharged during the first phases of eruption, Ordóñez (1947) states that

> some of them appeared to have been originally monzonite, others true granite, and a few porphyritic monzonite. These masses exhibited a very peculiar cellular structure and contained elongated fibers or fine filaments and delicate needles of colorless glass. The hornblende or augite that they contained appeared less altered than the feldspars, and the quartz looked as if it had actually been remelted.

Trask (1943), writing of the foreign fragments among the ejecta of February 28, 1943, says that they were angular, nonvesicular pieces of "a light medium-grained granitic rock that looked like diorite." Milton (1945) described white inclusions varying from dense porcelanic to fragile, clear, glassy pumice containing aggregates of shattered quartz and turbid areas probably representing partly vitrified feldspars. He noted that the contacts of these siliceous inclusions with the enclosing lava were extremely sharp, and the high silica content of the pumiceous glass suggested to him that the inclusions were fragments of rhyolitic breccia partly remelted by the Parícutin magma.

Schmitter (1945) described one inclusion with a hypidiomorphic granular texture composed of orthoclase, quartz, albite-oligoclase, andesine, magnetite, and accessory hornblende and biotite. This he classed as quartz monzonite.

All the inclusions collected by the writer between November 1944 and May 1945 are cellular, pumiceous, angular fragments measuring up to 6 inches across. Almost all consist essentially of strained and cracked anhedral grains of quartz up to 3 millimeters across, orthoclase, occasionally a little microcline and oligoclase, and accessory grains of ore immersed in a matrix of spongy, colorless glass. None contains ferromagnesian minerals. Other inclusions, up to 4 inches across, are composed entirely of sugary quartz; both in the field and under the microscope these resemble dense quartzites.

In the partly vitrified inclusions, the refractive index of the clear glass ranges from 1.490 to 1.502 ± .002. Probably the glass developed mainly by vitrifaction of potash feldspar and oligoclase and partly by solution of quartz. Spongy relics of feldspar can be seen in all stages of conversion, and some quartz grains show corrosion and veining by glass. The rocks bear a notable resemblance to vitrified arkoses (buchites) like those found around the margins of volcanic necks in the Navajo-Hopi country of Arizona and New Mexico (Williams, 1936).

As Milton observed, there is a notable absence of reaction between most of the inclusions and the surrounding lava. Rims of diopside around xenocrysts of quartz, such as are common in basalts, were not detected. The only change noted around some inclusions was a slight brownish discoloration of the pumiceous glass within a few microns of the enclosing lava.

There is no means of telling whether the plutonic fragments came from a basement beneath the beds of the Zumpinito formation or from a stock intrusive into those beds. Nor is it certain that the quartzitelike inclusions are actually of plutonic origin; they may be products of some process of differentiation of the Parícutin magma not yet understood.

Finally, reference should be made to the discovery by Krauskopf of small inclusions of anhydrite among the products of the volcano in 1945. Anhydrite-bearing inclusions have been described by Kôzu (1934) among the pumice erupted by Komagatake in 1929. It does not seem probable that the anhydrite fragments from Parícutin are xenoliths derived from beds in the Zumpinito formation; more likely they owe their origin to fumarolic action on the walls of the conduit.

SUMMARY OF PETROGRAPHY

The lavas of post-Zumpinito age in the Parícutin region range from olivine-augite basalts through basaltic andesites to hornblende and pyroxene andesites. The oldest volcanoes, those of Cerros de Tancítaro, Cerros de San Marcos, Cerro del Aguila, and Cerros de Angahuan, are the largest and were built entirely by effusions of olivine-free pyroxene andesite. The next-oldest volcanoes, those forming Cerros de Los Hornos, also erupted pyroxene andesite, but in addition they discharged flows of olivine-bearing basaltic andesite.

Following the extinction of these volcanoes, there developed a younger series of cones characterized by a wider variety of flows. The variation did not follow a regular pattern; on the contrary, the most diverse types of lava were extruded in quick succession by closely spaced volcanoes. Most of the younger flows are olivine-bearing basaltic andesites essentially like those now pouring from Parícutin volcano itself. However, eruptions of olivine-free and olivine-poor andesites persisted at intervals to within a few thousand years ago, beginning with the augite andesites of Mesa de Huanárucua and the hornblende andesites of Mesa de Zirimóndiro, continuing with the hypersthene andesites of Cerro de Camiro and adjacent vents, and ending with the colossal outpourings of vitrophyric pyroxene andesite by the Cerros de Capacuaro volcano. Still later, copious flows of olivine-rich andesite escaped from Cerro de Surúndaro.

While these eruptions of andesite and basaltic andesite were going on, there was intermittent effusion of olivine basalt from widely scattered cones. First came the basalts related to the Cerros de Zirosto cones and Cerro de Tiripan, then those erupted by the youthful cones of Cerro de Capatacutiro and Cerro de Tzintzungo, and finally, perhaps within the present millennium, the basalts that issued from some of the Jabalí cones near Uruapan.

Petrographically the younger andesites and basalts of the Parícutin region closely resemble those composing most of the coeval volcanoes of the circum-Pacific belt, such as those described from other parts of Mexico (Burri, 1930), from Nicaragua (Burri and Sonder, 1936), Patagonia (Larsson, 1940), and the Cascade Range (Williams, 1932, 1933, and 1942). They also resemble the principal lavas of the Lesser Antilles (MacGregor, 1938).

Mineralogically these younger basalts and andesites are marked by the absence of biotite. Hornblende is confined to a few andesitic lavas, occurring as a minor porphyritic constituent in both the youngest and the oldest of the region, those of Cerros de Tancítaro and the Cerros de Capacuaro. Only in one andesite, that of Mesa de Zirimóndiro, does it form the principal ferromagnesian constituent. All of it is of the oxyhornblende variety, and generally it is either rimmed or almost wholly replaced by augite and granular ore.

Hypersthene is generally more plentiful in the more siliceous lavas. It is absent from all the basalts and from many of the basaltic andesites. In other basaltic andesites it is present only as microliths, usually varying in amount between 1 and 6 percent of the total volume, though in the most crystalline of the lavas from Parícutin it makes up 10 percent of the volume. In the olivine andesite of Cerro de Surúndaro it is extremely rare and minute; in the andesites of Cerro de Zirimóndiro and Mesa de Huanárucua it is absent. It forms phenocrysts only in the olivine-poor and olivine-free andesites. The composition shows no correlation with the bulk composition of the containing lavas, the percentage of $FeSiO_3$ varying between 14 and 40. Among the phenocrysts of the andesites of Cerros de Tancítaro, the percentage of ferrosilite ranges from 32 to 38; in those of the andesites of Cerros de Angahuan, it approximates 25; in those of Cerro del Aguila, there is a normal zoning from 14 to 34. The larger hypersthenes of the andesites of Cerros de Los Hornos contain 14 to 18 percent of the ferrosilite molecule, whereas the microliths carry 22 to 26 percent. In the andesites of Cerros de Capacuaro the hypersthene is more uniform, the ferrosilite content departing little from 26 percent. The greatest variation and the only examples of reverse zoning in hypersthene are to be seen in the olivine andesites of Cerro de Surúndaro, in which some of the small prisms have cores with 40 percent $FeSiO_3$ enclosed by rims with only 20 percent. Among the basaltic andesites the hypersthene grains are generally too small for proper optical reading, but in one of the flows of Cerro de Canicjuata the mineral contains 32 percent $FeSiO_3$ and in a glass-rich flow from Parícutin the mineral carries 28 percent of this molecule. Only in one specimen, an andesite from Cerros de Tancítaro, does the hypersthene show any alteration. Here it is partly changed to magnetite and hematite, presumably as a result of fumarolic action.

Monoclinic pyroxene is present in every lava examined. It is pale yellowish green and without sensible pleochroism. Rarely the optic angle is as low as 47° and as high as 60°; normally it varies between 52° and 58°. The extinction angles, Z to c, range from 41° to 45°. In other words, pigeonite is absent. According to the classification suggested by Benson (1944), the clinopyroxenes of the Parícutin region are augites. None falls into his category of subcalcic augite. All are included in the field of olivine basalt clinopyroxenes, as distinguished from tholeiitic clinopyroxenes by Wager and Deer (1939). They are referred to here as iron-poor diopsidic augites with approximately 30 to 50 percent by weight of the wollastonite and enstatite molecules.

Larsson (1940), in studying somewhat similar lavas from the Andes of Patagonia, observed that the clinopyroxenes in olivine-free andesites are usually richer in iron and poorer in lime than they are in olivine-bearing basalts. He noted further that lime-rich diopsidic augites are predominantly associated with magnesia-rich olivines and that hypersthene occurs mainly with clinopyroxenes richer in iron and with intermediate content of lime. All that can be said of the augites of the Parícutin region is that they tend to be richer in lime among the basalts. It would require far more study than has been possible to correlate their variations with those of the hypersthenes and olivines and to show how the porphyritic augites differ from the microliths.

There is no tendency for the augite to be more porphyritic or more plentiful in any particular group of lavas, but no flows contain less than do those of Parícutin volcano itself. Euhedral forms are least common among the basaltic lavas.

Alteration of augite is extremely rare. In one specimen of andesite from Cerro de Tancítaro and in the pink variety of the andesite of Mesa de Huanárucua, the mineral shows marginal discoloration, presumably caused by oxidation of iron under the influence of residual vapors.

The mineral olivine is absent from all the andesites of the region except those erupted by Cerro de Surúndaro and by Cerro de Camiro and adjacent vents. Even in these it rarely makes up more than 4 percent of the volume. Among the basaltic andesites it generally constitutes between 3 and 7 percent by volume; among the basalts it increases in amount to between 6 and 14 percent. There is, however, no corresponding increase in size. Generally the mineral occurs as ovoid phenocrysts between 0.5 millimeter and 2 millimeters across; exceptionally it reaches a maximum length of 4 millimeters. Typical forms have been illustrated by Schmitter (1945). In many basaltic andesites, especially those of Cerro de Cutzato and Parícutin volcano, the crystals are tabular parallel to the base and elongated along the *b* axis; in these and many other basaltic andesites the larger phenocrysts are deeply embayed by magmatic corrosion, whereas the smaller ones are approximately spheroidal.

The olivines range in composition from pure forsterite to Fo_{50}, as calculated from optic angles. They tend to be more magnesian in the basalts, among which the range is from Fo_{72} to Fo_{98}. Among the basaltic andesites the range is from Fo_{50} to Fo_{100}; in the olivine andesite of Cerro de Surúndaro it is from Fo_{67} to Fo_{76}.

Particularly striking is the wide variation within individual specimens of lava, adjacent crystals often differing in forsterite content by as much as 10 to 15 percent. Nowhere is the variation greater than in the lavas of the new volcano. For instance, in the glass-rich variety of lava from Parícutin volcano described in pages 256–258, the larger olivines vary between Fo_{63} and Fo_{84}, whereas the smaller ones vary between Fo_{82} and Fo_{90}. In the more crystalline variety the larger olivines range between Fo_{76} and Fo_{82}; the smaller vary from Fo_{82} to Fo_{92}. One phenocryst has a core of Fo_{87} enclosed by a rim of Fo_{72}. These measurements serve to account for the strong corrosion embayments seen in many of the olivine phenocrysts of Parícutin, the larger crystals commonly being more ferriferous than the late-forming, smaller granules. It may be that the lack of equilibrium denoted by this resorption of the phenocrysts indicates a sharp rise in temperature of the Parícutin magma upon extrusion.

In other basaltic andesites all the zoning in the olivines is normal. For example, in a lava from Cerro del Aire, one phenocryst has a core of pure forsterite and a rim of Fo_{72}; another has a core of Fo_{67} surrounded by a thin shell of Fo_{50}.

In most lavas the olivine is quite fresh, but in the basaltic andesites of Cerro de Cutzato and Cerro Prieto especially, the effects of oxidation and hydration are pronounced. Here much of the olivine is either marginally or almost entirely replaced by magnetite and hematite. In other crystals the fresh cores grade outward through hydrated olivine of lower birefringence to green antigorite that may in turn be enclosed by rims of magnetite. Peripheral alteration of olivine to antigorite and hematite is also to be seen in the lava of Cópitiro, but development of iddingsite among the post-Zumpinito lavas was observed only in some of the basalts erupted from Cerros de Zirosto. Even here the mineral is restricted to the rims of the olivines. Among the basalts of the Zumpinito formation from Cerro Colorado (pp. 232–233), iddingsite is extremely abundant and much of it occurs in the cores of the olivines. Replacement of olivine by talc was not observed.

Turning next to the silica minerals, it should be repeated that porphyritic quartz is completely absent. Cryptocrystalline quartz may be present in the dense groundmass of the pilotaxitic andesites of Cerros de Tancítaro and Cerros de San Marcos and in the matrix of a few basaltic andesites such as those of Cerro de Cutzato. Cristobalite and, in smaller amount, tridymite are minor constituents in the pores of many andesites of Cerros de Tancítaro, but both minerals are surprisingly rare in other lavas of the region considering how plentiful they are in the groundmass of otherwise similar basaltic andesites and basalts of the circum-Pacific volcanic belt. Opal and chalcedony appear to be entirely lacking.

Orthoclase has not been identified with certainty in any of the lavas, but on the basis of chemical analyses its presence is suspected in the cryptocrystalline matrix of several andesites.

Plagioclase is invariably the most abundant mineral in all lavas. No general rule can be established relating its size either to its own composition or to that of the enclosing lavas, except that in the basaltic andesites it is exceptional to find crystals more than 1 millimeter in length. Among the olivine-free andesites, the oldest—that is, those of Cerros de Tancítaro, Cerros de San Marcos, and Cerro del Aguila—are especially rich in porphyritic plagioclase, many crystals reaching a length of 3 millimeters. Among the younger andesites feldspar laths more than 0.5 millimeter long are unusual. Among most of the basaltic lavas, also, it is rare to find laths more than 0.5 millimeter long; however, in those of Cerro de Tzintzungo phenocrysts reach a length of 1.5 millimeters, and in those of Cerro de Capatacutiro they attain a length of 5 millimeters.

In composition the feldspar ranges from An_{50} to An_{80}. A rough correlation can be drawn between the silica content of the lavas and the anorthite content of the included feldspars. Thus, among the basalts, the range is from An_{65} to An_{80}; among the basaltic andesites, from An_{52} to An_{80}; among the olivine andesites, from An_{55} to An_{62}; and among the olivine-free andesites, from An_{50} to An_{70}.

Zoning is particularly marked in the coarsely porphyritic, older pyroxene andesites. In these, many of the phenocrysts show strong oscillatory zoning throughout, and in some the zoning is reversed. The groundmass feldspars in these lavas are always of about the same composition or more sodic than the rims of the phenocrysts. Among the younger andesites, zoning of the feldspars is less distinct and is usually normal rather than normal oscillatory. In view of Wenk's observation (1945) on the influence of the crystallization of hornblende on the development of oscillatory zoning in the feldspars, it may be noted that the plagioclase in the hornblende andesite of Mesa de Zirimóndiro shows only very weak normal zoning. Among the basaltic andesites and basalts, oscillatory zoning of the plagioclase is not as common as normal zoning; in the lavas of Parícutin itself, oscillatory zoning of feldspar is extremely rare and even normal zoning is only weakly developed. Usually, as Foshag and Schmitter have observed, the albite content increases as the feldspar microliths diminish in size.

Iron ores are invariably present. In the older, pilotaxitic andesites they form subhedral microphenocrysts, as they do in the holocrystalline basaltic andesites and basalts. Although seldom absent as inclusions within the early forming olivines, they developed mostly at a late stage, and in the glassy lavas they occur as irresolvable specks and dendritic clusters. Only in the pahoehoe basalt of Cerro de Capatacutiro was ilmenite recognized with certainty; in the other lavas the ore appears to be weakly titaniferous magnetite. Except where fumarolic action has converted part of the ore to hematite, as in the pinkish lavas of Mesa de Zirimóndiro, Mesa de Huanárucua, and Cerro de Cutzato, the mineral is always fresh.

Apatite was identified as a minor accessory in a few flows, being most plentiful in the basaltic andesite of Cerro de Cutzato.

Reference has already been made to the occurrence of tridymite, cristobalite, and hematite in many lavas as products of fumarolic activity, but nothing is more striking than the complete absence in all lavas of the Parícutin region of minerals resulting from the action of hydrothermal solutions, such as kaolin, sericite, alunite, calcite, and chlorite. In contrast to many other regions of recent volcanism in Mexico and elsewhere in the circum-Pacific belt, there exists in the Parícutin region no trace of former hot-spring or solfataric activity. By analogy, none should be expected to follow when the eruptive phase of Parícutin itself comes to an end.

PETROCHEMISTRY

The lavas of the Neo-Volcanic Zone of Mexico, including those of the Parícutin region, belong to the calc-alkalic igneous series as defined by Peacock (1931). The alkali-lime index—that is, the silica percentage at which the content of lime equals that of soda plus potash—is 60. For coeval lavas in the Cascade volcanic belt the indices are as follows: Crater Lake, 62; Mount St. Helens, 63.2; Mount Shasta, 63.7; and the Lassen Peak region, 63.9. These belong to Peacock's calcic series, as do the lavas of the Lesser Antilles and the Patagonian Andes. On the other hand, the Mexican lavas closely resemble those of Nicaragua, for which the index also approximates 60.

According to the classifications proposed by Niggli (1923 and 1936), the Mexican lavas range from the quartz dioritic magma type through the normal dioritic to the normal gabbrodioritic. In brief, they are dominantly calc-alkalic basalts and andesites. Burri's detailed study (1930) emphasizes their similarity to most of the circum-Pacific lavas and indicates further their affinities with the slightly alkalic type represented by the San Francisco Mountains volcanic suite. Along with Sonder (1936), Burri also examined the lavas of Nicaragua and the Panama Canal Zone, finding that there, as in Mexico, the younger flows tend to be more calcic than most of the lavas of Tertiary age.

Table 2 shows the general resemblance of the lavas of the Parícutin region and of Nicaragua to those of Mont Pelée, Lassen Peak, and the Sierra Nevada and demonstrates how all these differ from the lavas of the North American Cordillera. Figure 90, in which the *si* values are plotted against the *mg* values, emphasizes the similarity between the flows of the Parícutin region and those of the Pelée-Lassen areas and the Sierra Nevada. The lower *mg* values of the Nicaraguan lavas are reflected partly by the more ferriferous character of the pyroxenes and olivines.

The low *k* values of the rocks of the Parícutin region are only to be expected in view of the scarcity of modal orthoclase and the absence of biotite. Low *k* values also characterize the lavas of Nicaragua, the

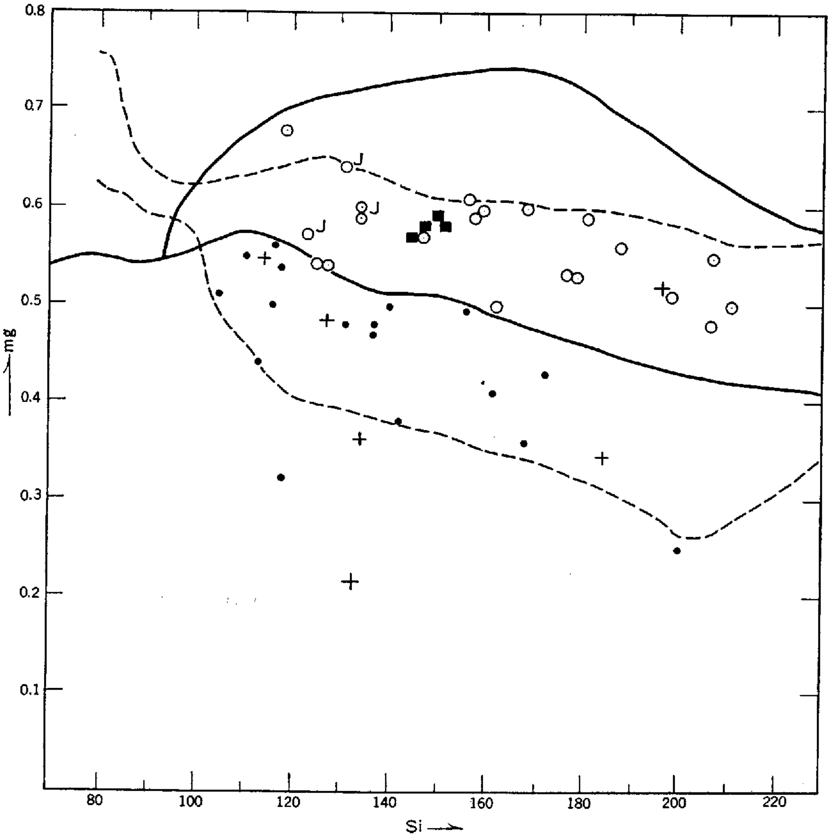


FIGURE 90.—*Si–mg* diagram, Mexican and other lavas. Open circles represent lavas of the Parícutin region and Jorullo (J); dots, lavas of Nicaragua; crosses, lava of the Panama Canal Zone; squares, lavas of the Parícutin volcano. Area between solid lines includes all but two lavas of the Sierra Nevada-Lassen Peak area, California. Area between dashed lines includes all other young lavas of Mexico not indicated separately. Diagram partly after C. Burri and R. A. Sonder, Zeitschrift für Vulkanologie, Band 17, p. 87, 1936.

TABLE 2.—*Niggli values for lavas of the Parícutin region and other areas of Pacific type*

[Values for other areas taken from C. Burri and R. A. Sonder, Zeitschrift für Vulkanologie, Band 17, p. 85, 1936]

Region	si	al	fm	c	alk	al-alk	c-(al-alk)	qz
Parícutin	120	24	45	22	8	16	+6	−10
Nicaragua		25	41	28	6	19	+9	−12
Pelée-Lassen		25	41	26	8	16	+10	−12
Sierra Nevada		22.5	43	24.5	9.5	13	+11.5	−16
North American Cordillera		22.5	42.5	25	10	12.5	+12.5	−20
Parícutin	150	29	36	22.5	11	18	+4.5	+5
Nicaragua		29	34	26	11	18	+8	+6
Pelée-Lassen		28.5	36	25	10	18.5	+6.5	+10
Sierra Nevada		27	36	24	13	14	+10	−2
North American Cordillera		27	35	23	15	12	+11	−10
Parícutin	200	35	28	21.5	15	20	+1.5	+40
Nicaragua		35	26	21	18	17	+8	+28
Pelée-Lassen		34	28	22.5	15	19	+6.5	+40
Sierra Nevada		33	28	21	18	15	+10	+28
North American Cordillera		34	26	18	22	12	+11	+12

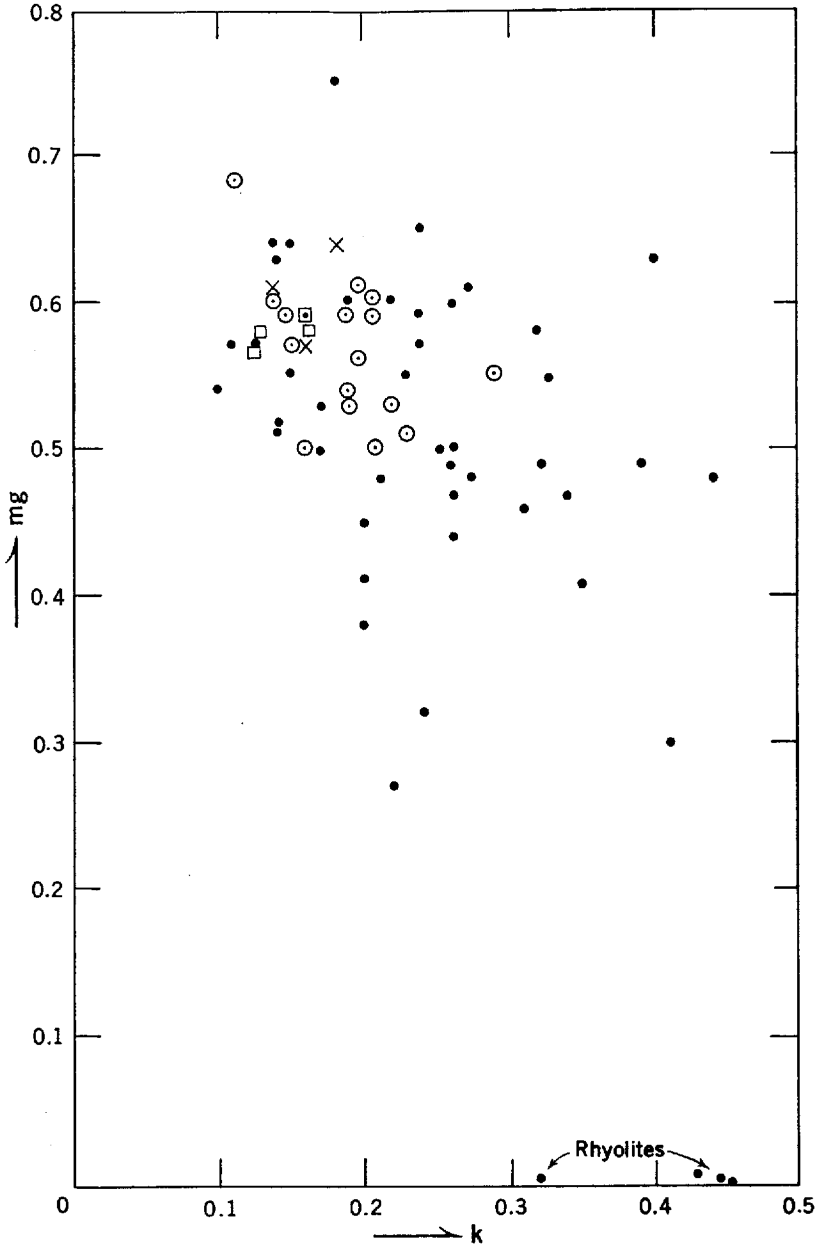


FIGURE 91.—*K–mg* diagram, Neo-Volcanic Zone of Mexico. Crosses represent lavas of Jorullo; circles with dots, lavas of the Parícutin region; squares, lavas of Parícutin volcano; dots, other lavas of the Neo-Volcanic Zone.

Lesser Antilles (MacGregor, 1938), and Crater Lake (Williams, 1942). The *k–mg* ratios (fig. 91) of the Parícutin region are essentially the same as those of the Cascade and West Indian lavas. The similarity extends to the character of the normative feldspar (fig. 92).

Certain peculiarities serve, however, to distinguish the lavas of the Parícutin region from coeval flows in other parts of the Neo-Volcanic Zone of Mexico. Examination of figures 93 and 94 shows that the former are richer in alumina and poorer in both total iron and potash than the latter. With respect to these constituents, the lavas of the Parícutin region are almost identical with those of Lassen Peak and Crater Lake. The magnesia and soda curves of the variation diagrams are almost the same for all. Just why the lavas of the Parícutin

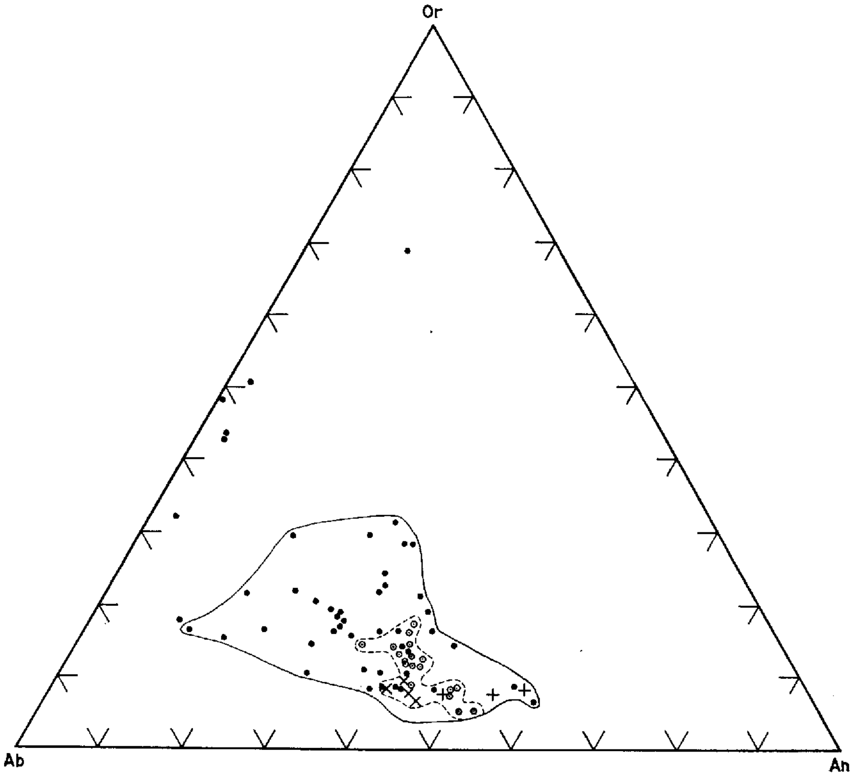


FIGURE 92.—Normative feldspar diagram of Mexican lavas. Dots outside solid line represent rhyolites of Mexico of late Tertiary age; dots inside line, coeval andesites and basalts. Dots within circles represent lavas of the Parícutin region. Diagonal crosses represent lavas of Parícutin volcano; other crosses represent products of Jorullo volcano.

region are richer in alumina and poorer in iron than other young lavas of Mexico is not clear. Table 2 shows that the c' [c-(al-alk)] values of the lavas of the Parícutin region are strikingly low, indicating poverty of normative diopside, yet the modal clinopyroxenes are rich in the wollastonite molecule. It may be that the high alumina content of these lavas reflects a tendency toward more plagioclase and less pyroxene; on the other hand, it may be related in part to the composition of the augites; but until more is known concerning the

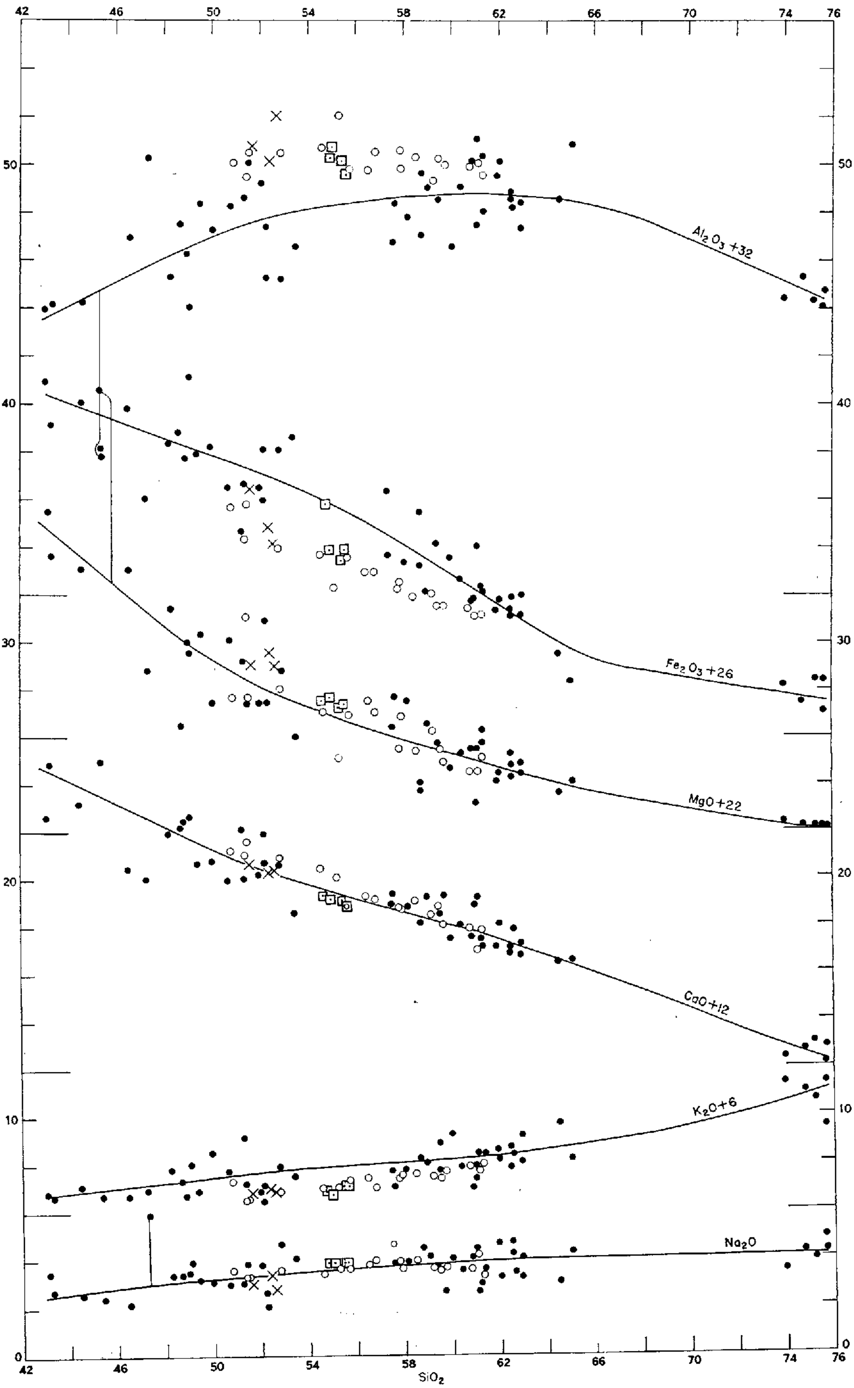


FIGURE 93.—Variation diagram of Mexican lavas. Black dots represent lavas of Neo-Volcanic Zone outside Michoacán; open circles, lavas of the Parícutin region; crosses, lavas and bombs of Jorullo volcano; squares, lavas of Parícutin volcano.

influence of the sesquioxides on the optical properties of the clinopyroxenes, it is unwise to speculate further.

As to the general trend of differentiation among the lavas of Parícutin and vicinity, there appears to be no reason to doubt that the principal control was crystal fractionation. In some andesites the wide range in composition and the reverse zoning among the feldspar phenocrysts may have resulted from mingling of magmas prior to extrusion, but there is no proof that differentiation was influenced by con-

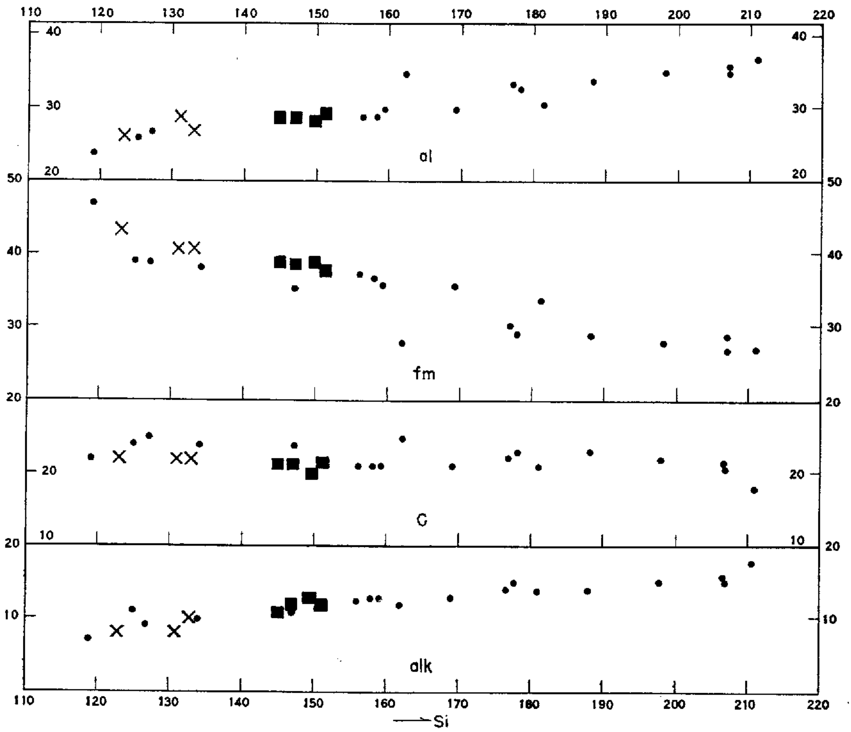


FIGURE 94.—Niggli diagram of Mexican lavas. Dots represent older lavas of the Parícutin region; crosses, lavas of Jorullo; squares, lavas of Parícutin volcano.

tamination of magma in consequence of selective solution of older rocks. At least under near-surface conditions there has been virtually no reaction between the magma of the Parícutin volcano and its inclusions of quartz monzonite.

No evidence has been found to suggest that differentiation took place in shallow feeding chambers; more likely the volcanoes of the Parícutin region were fed by narrow, vertical dikes tapping sources far below. Seismic studies may throw more light on this fundamental problem. At present pitifully little is known concerning the origin of volcanic magmas and the forces that impel them to the surface.

Finally, reference should be made to the products of the new volcano. The four most reliable analyses of lavas of Parícutin volcano are presented in table 3. Their similarity is striking. Less reliable analyses of lavas and ashes from Parícutin have been published elsewhere (Flores et al., 1945); these have been omitted in preparing the variation diagrams.

TABLE 3.—*Analyses of lavas from Parícutin volcano*

	1	2	3	4
Constituents				
SiO_2	54.88	55.04	55.51	55.59
Al_2O_3	18.38	18.82	18.19	17.72
Fe_2O_3	1.31	1.92	1.63	1.33
FeO	5.97	5.69	5.38	5.99
MgO	5.57	5.68	5.31	5.60
CaO	7.40	7.17	7.19	6.99
Na_2O	3.88	3.88	3.92	4.00
K_2O	.86	.85	1.10	1.13
H_2O+	.13	.16	.08	.03
H_2O-	.05		.01	.04
TiO_2	.95	.94	.97	1.05
P_2O_5	.29	.21	.31	.36
MnO	.13	.07	.12	.13
Totals	99.80	100.53	99.72	99.96
Niggli values				
si	147	145	151	150
al	29	29	29	28.5
fm	38.5	39	38	39
c	21	21	21	20
alk	11.5	11	12	12.5
k	.125	.125	.16	.16
mg	.58	.57	.58	.59
qz	+1	+1	+3	0

1. The first flow. Erma Chadbourn, analyst.
2. Lava of Feb. 22, 1943. Includes 0.04 percent S and 0.06 percent BaO. Charles Milton, analyst.
3. Sapichu flow. Erma Chadbourn, analyst.
4. Ahuán flow. Erma Chadbourn, analyst.

On the basis of their *qz* values and the presence of normative quartz, the lavas of Parícutin are here classed as olivine-bearing basaltic andesites. Figure 94 shows that their composition falls on the general curves for the Parícutin region as a whole. Among adjacent lavas they resemble most closely the basaltic andesites of Cerro del Aire and Cerro de Cutzato, but they do not differ greatly from the recent flows of Cerro Prieto and the final outflow, less than a century ago, of the Cerros del Jabalí cone cluster. Their resemblance to the olivine-free hornblende andesite of Mesa de Zirimóndiro also deserves to be noted. The products of Jorullo are less siliceous and, having negative *qz* values of 1 to 9, are to be classed as olivine basalts.

864334—50——8

REFERENCES CITED

Barnes, V. E., and Romberg, Frederick, 1948, Observations of relative gravity at Parícutin volcano: Geol. Soc. America Bull., vol. 59, pp. 1019–1026.

Benson, W. N., 1944, The basic igneous rocks of eastern Otago, part 4: Royal Soc. New Zealand Trans., vol. 74, pp. 71–123.

Blásquez, L., and Garcia, R. L., 1946a, Hidrogeológia y minerales no-metálicos del Estado de Tlaxcala: Inst. geol. México Anales, vol. 8.

——— 1946b, Hidrogeológia y minerales no-metálicos del Estado de Michoacán: Inst. geol. México Annales, vol. 9.

Bodle, R. R., 1945, Parícutin magnetic survey: Am. Geophys. Union Trans., 25th Ann. Mtg., pt. 4, pp. 629–630.

Bullard, F. M., 1947, Studies on Parícutin volcano, Michoacán, Mexico: Geol. Soc. America Bull., vol. 58, pp. 433–449.

Burri, Conrad, 1930, Petrographische Beschreibung einiger von Immanuel Friedlaender in Mexiko gesammelter vulkanischer Gesteine: Zeitschr. Vulkanologie, vol. 13, pp. 165–192.

Burri, Conrad, and Sonder, R. A., 1936, Beiträge zur Geologie und Petrographie des jungtertiären and rezenten Vulkanismus in Nicaragua: Zeitschr. Vulkanologie, vol. 17, pp. 34–92.

De la O. Carreño, Alfonso, 1943, El volcán de Parícutin en las primeras fases de su erupción: Irrigación en Mexico, vol. 24, no. 4, pp. 49–80.

Edwards, A. B., 1938, The formation of iddingsite: Am. Mineralogist, vol. 23, pp. 277–281.

Flores, Teodoro, 1920, Estudio geológico-minero de El Oro y Tlalpujahua: Inst. geol. México Bol. 37.

Flores, Teodoro, and others, 1945, El Parícutin, Estado de Michoacán, México, D. F., Instituto de Geología.

———, 1946, Geología minera de la región N. E. del Estado de Michoacán: Inst. geol. México Bol. 52.

Foshag, W. F., and Henderson, E. P., 1946, Primary sublimates at Parícutin volcano: Am. Geophys. Union Trans., vol. 27, pp. 685–686.

Foslie, S., 1931, On antigorite-serpentine from Ofoten: Norsk geol. tidssk., vol. 12, pp. 219–245.

George, W. O., 1924, The relation of the physical properties of natural glasses to their chemical composition: Jour. Geology, vol. 32, pp. 353–372.

González R., Jenaro, and Foshag, W. F., 1947, The birth of Parícutin: Smithsonian Inst. Ann. Rept. for 1946, pp. 223–234.

Graton, L. C., 1945a, The genetic significance of Parícutin: Am. Geophys. Union Trans., vol. 26, pp. 249–254.

———, 1945b, Ciertos aspectos genéticos del Parícutin, in El Parícutin, Estado de Michoacán, pp. 61–91, México, D. F., Instituto de Geología.

Hobbs, W. H., 1944, New volcanoes and a new mountain range: Science, vol. 99, pp. 287–290.

Jones, A. E., 1946, Notes on Parícutin lava: Am. Geophys. Union Trans., vol. 27, pp. 523–525.

Keller, Fred, Jr., 1946, The magnetic work of the United States Coast and Geodetic Survey at Parícutin volcano, Michoacán, Mexico: Am. Geophys. Union Trans., vol. 27, pp. 350–363.

Kellum, L. B., 1944, Geologic history of northern Mexico: Am. Assoc. Petroleum Geologists Bull., vol. 28, pp. 301–325.

Kennedy, G. C., 1946, Activity of Parícutin volcano from April 12 to May 3, 1946: Am. Geophys. Union Trans., vol. 27, pp. 410–411.

Kôzu, S., 1934, The great activity of Komagatake [Japan] in 1929: Min. pet. Mitt., Band 45, pp. 133–174.

Krauskopf, Konrad, 1946a, Notes on activity of Parícutin volcano during December 1945: Am. Geophys. Union Trans., vol. 27, p. 119.

———, 1946b, Notes on activity of Parícutin volcano during January 1946: Am. Geophys. Union Trans., vol. 27, p. 218.

———, 1948a, Mechanism of eruption at Parícutin volcano, Mexico: Geol. Soc. America Bull., vol. 59, pp. 711–732.

———, 1948b, Lava movement at Parícutin volcano, Mexico: Geol. Soc. America Bull., vol. 59, pp. 1267–1283.

Krauskopf, Konrad, and Williams, Howel, 1946, The activity of Parícutin during its third year: Am. Geophys. Union Trans., vol. 27, pp. 406–410.

Larsson, Walter, 1940, Petrology of interglacial volcanics from the Andes of northern Patagonia: Upsala Univ. Geol. Inst. Bull., vol. 28, pp. 191–405.

MacGregor, A. G., 1938, The volcanic history and petrology of Montserrat: Royal Soc. London Philos. Trans., ser. B, vol. 229, pp. 1–90.

Milton, Charles, 1945, Notes on volcanic rocks from Parícutin, Mexico: Am. Geophys. Union Trans., vol. 25, pp. 618–621.

Niggli, Paul, 1923, Gesteins- und Mineralprovinzen, Band 1, Berlin.

———, 1936, Die Magmentypen: Schweizer min. pet. Mitt., vol. 16, pp. 335–399.

Ordóñez, Ezequiel, 1906, Le Jorullo, 10ᵉ Cong. géol. internat., Mexico, Guide Exc., no. 11.

———, 1910, Le Pic de Tancítaro, Michoacán: Soc. cient. Antonio Alzate Mem., vol. 30, pp. 11–17.

———, 1943, The new volcano of Parícutin, pp. 62–78, Texas Univ., Inst. Latin Am. Studies.

———, 1947, El volcán de Parícutin, pp. 181, Mixcoac, D. F., Editorial Fantasía.

Peacock, M. A., 1931, Classification of igneous rock series: Jour. Geology, vol. 39, pp. 54–67.

Perez Peña, Adán, 1946, Informe sobre el volcán de Parícutin: Bol. minas y petróleo, vol. 16, no. 10, pp. 3–13.

Philipp, H., 1936, Bewegung und Textur in magmatischen Schmelzflüssen: Geol. Rundschau, Band 27, pp. 321–365.

Robles Ramos, Ramiro, 1942, Orogénesis de la República Mexicana: Irrigación en México, vol. 23, no. 3, pp. 7–61.

———, 1943, El volcán de Parícutin y el Neo-Volcanismo Mexicano: Irrigación en México, vol. 24, no. 4, pp. 1–45.

Schmitter, Eduardo, 1945, Estudio petrográfico de lavas y productos piroclásticos, in Flores, Teodoro, and others, El Parícutin, Estado de Michoacán, pp. 113–131, México, D. F., Instituto de Geología.

Segerstrom, Kenneth, 1950, Erosion studies at Parícutin: U. S. Geol. Survey Bull. 965–A.

Segerstrom, Kenneth, and Gutiérrez, Celedonio, 1947, Activity of Parícutin volcano from May 4 to September 18, 1946: Am. Geophys. Union Trans., vol. 28, pp. 559–566.

Storm, Marian, 1945, Enjoying Uruapan, p. 105, Mexico.

Trask, P. D., 1943, The Mexican volcano Parícutin: Science, vol. 98, pp. 501–505.

Wager, L. R., and Deer, W. A., 1939, The petrology of the Skaergaard intrusion: Meddelelser om Grönland, Band 105, Nr. 4.

Waitz, Paul, El nuevo volcán de Parícutin: Irrigación en México, vol. 24, no. 4, pp. 5–16.

Wenk, E., 1945, Die Koexistenzbeziehungen zwischen Hornblende, Biotit und Feldspäten und die Bedeutung der oszillierenden Zonarstruktur: Schweizer min. pet. Mitt., Band 25, pp. 141–164.

White, D. E., 1945, Parícutin's cyclic activity: Am. Geophys. Union Trans., vol. 25, p. 621–628.

Wilcox, R. E., 1947a, The activity of Parícutin volcano from September 18 to November 30, 1946: Am. Geophys. Union Trans., vol. 28, pp. 567–572.

———, 1947b, The activity of Parícutin volcano from December 1, 1946, to March 31, 1947: Am. Geophys. Union Trans., vol. 28, pp. 725–731.

———, 1948a, The activity of Parícutin volcano from April 1 to July 31, 1947: Am. Geophys. Union Trans., vol. 29, pp. 69–74.

———, 1948b, The activity of Parícutin volcano from December 1, 1947, to March 31, 1948: Am. Geophys. Union Trans., vol. 29, pp. 355–360.

Wilcox, R. E., and Gutiérrez, Celedonio, 1948, The activity of Paricutin volcano from April 1 to July 31, 1948: Am. Geophys. Union Trans., vol. 29, pp. 877–881.

Wilcox, R. E., and Shoup Oropeza, Samuel, 1948, The activity of Parícutin volcano from August 1 to November 30, 1947: Am. Geophys. Union Trans., vol. 29, pp. 74–79.

Williams, Howel, 1932, Geology of the Lassen Volcanic National Park, Calif.: California Univ., Dept. Geol. Sci., Bull., vol. 21, pp. 195–385.

———, 1933, Mount Thielsen, a dissected Cascade volcano: California Univ., Dept. Geol. Sci., Bull., vol. 23, pp. 195–214.

———, 1935, Newberry volcano of central Oregon: Geol. Soc. America Bull., vol. 46, pp. 253–304.

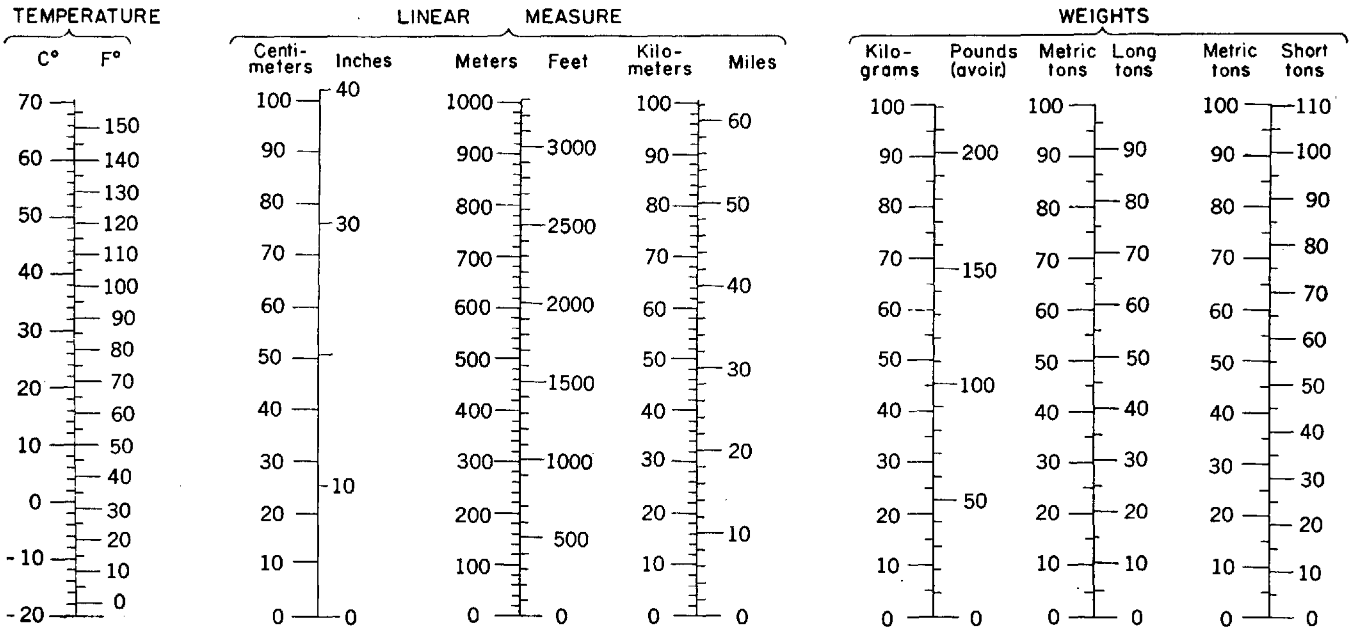
———, 1936, Pliocene volcanoes of the Navajo-Hopi country: Geol. Soc. America Bull., vol. 47, pp. 157–159.

———, 1942, Geology of Crater Lake National Park, Oreg.; Carnegie Inst. Washington Pub. 540.

———, 1945, Geologic setting of Parícutin volcano: Am. Geophys. Union Trans., vol. 26, pp. 255–256.

Zies, E. G., 1946, Temperature measurements at Parícutin volcano: Am. Geophys. Union Trans., vol. 27, pp. 178–180.

METRIC EQUIVALENTS



1 cm. = 0.3937 in.
1 in. = 2.5400 cm.

1 m. = 3.2808 ft.
1 ft. = 0.3048 m.

1 km. = 0.6214 mile
1 mile = 1.6093 km.

1 sq. m. (m2) = 1.20 sq. yd.
1 hectare (100x100m.) = 2.47 acres
1 cu. m. (m3) = 1.31 cu. yd.

1 kg. = 2.2046 lb.
1 lb. = 0.4536 kg.

1 metric ton = 0.9842 long ton
1 metric ton = 1.1023 short tons
1 metric ton = 2,205 lb.
1 long ton = 1.0161 metric ton
1 short ton = 0.9072 metric ton

INDEX

O

Petrology of Parícutin Volcano Mexico

By RAY E. WILCOX

GEOLOGIC INVESTIGATIONS IN THE PARÍCUTIN AREA, MEXICO

GEOLOGICAL SURVEY BULLETIN 965-C

Prepared in cooperation with the Secretaría de la Economía Nacional de México, Dirección de Minas y Petróleo, and the Universidad Nacional Autónoma de México, Instituto de Geología, under the auspices of the Foreign Operations Administration, Department of State

---

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1954

UNITED STATES DEPARTMENT OF THE INTERIOR

Douglas McKay, *Secretary*

GEOLOGICAL SURVEY

W. E. Wrather, *Director*

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C. - Price 30 cents (paper cover)

CONTENTS

ILLUSTRATIONS

TABLES

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.

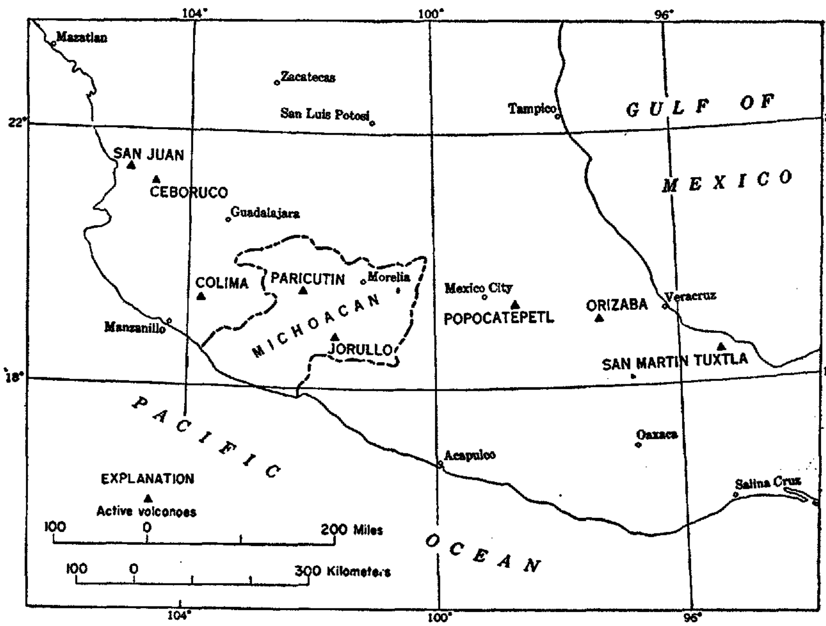


FIGURE 95.—Map of central Mexico showing location of Parícutin and other volcanoes active since 1519.

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 6¼ 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

[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

285997—54——2

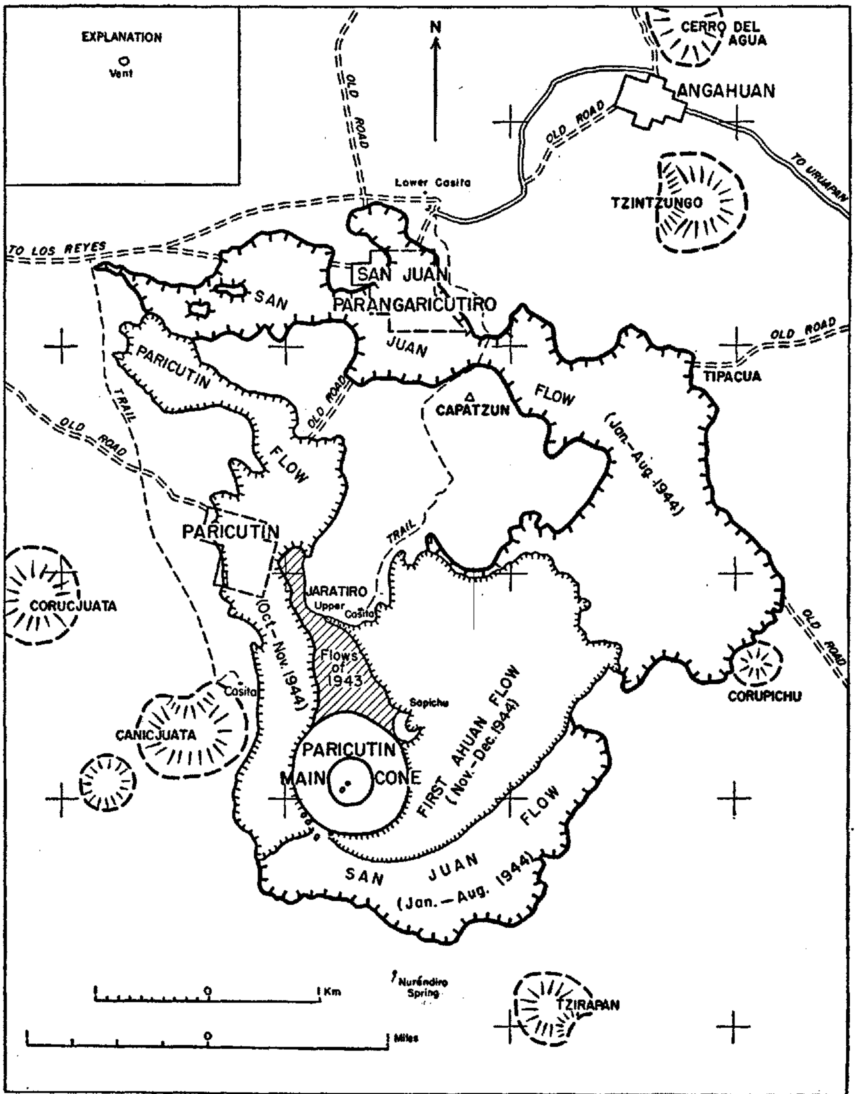


FIGURE 96.—Area covered by lavas of Parícutin volcano to end of 1944.

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

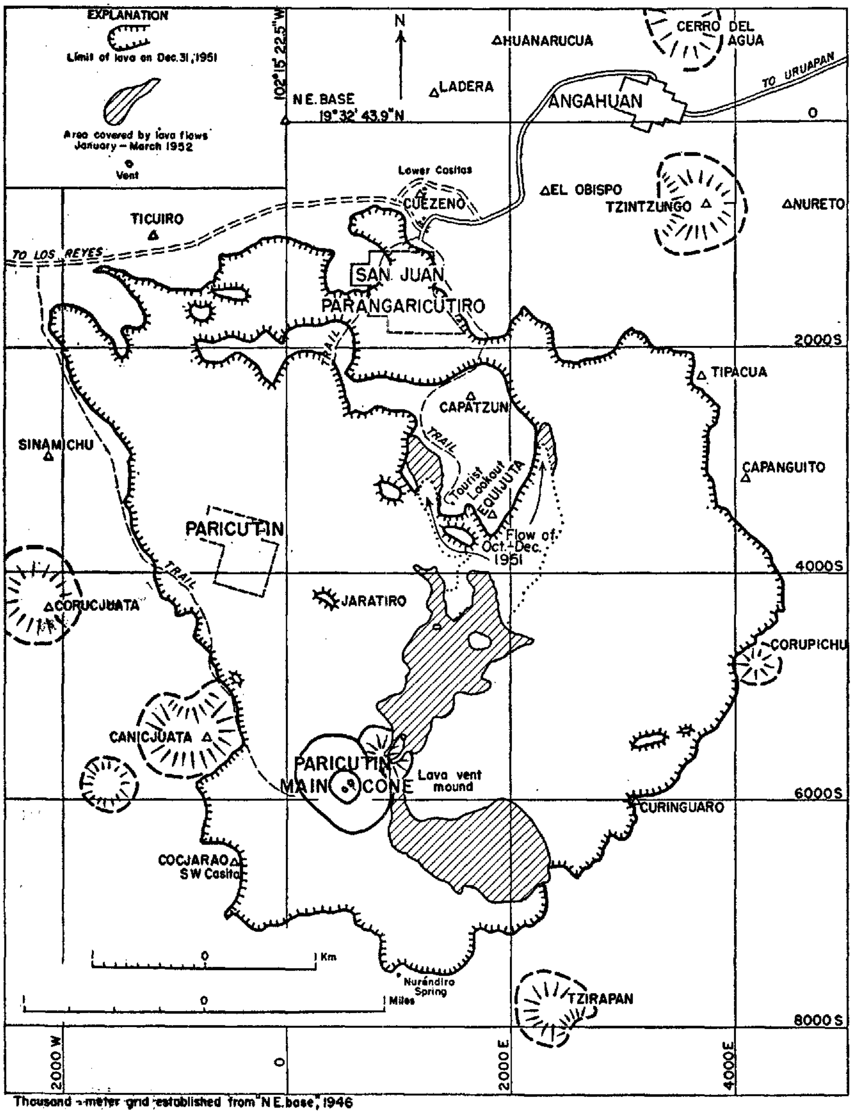


Figure 97.—Area covered by lavas of Parícutin volcano to end of 1952 (after Fries and Gutiérrez, 1954).

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 3596×10^6 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 ± 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.

285997—54——3

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 (H₂O+ and H₂O−)	.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. Hernández 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. Hernández 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.

PLATE 10

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

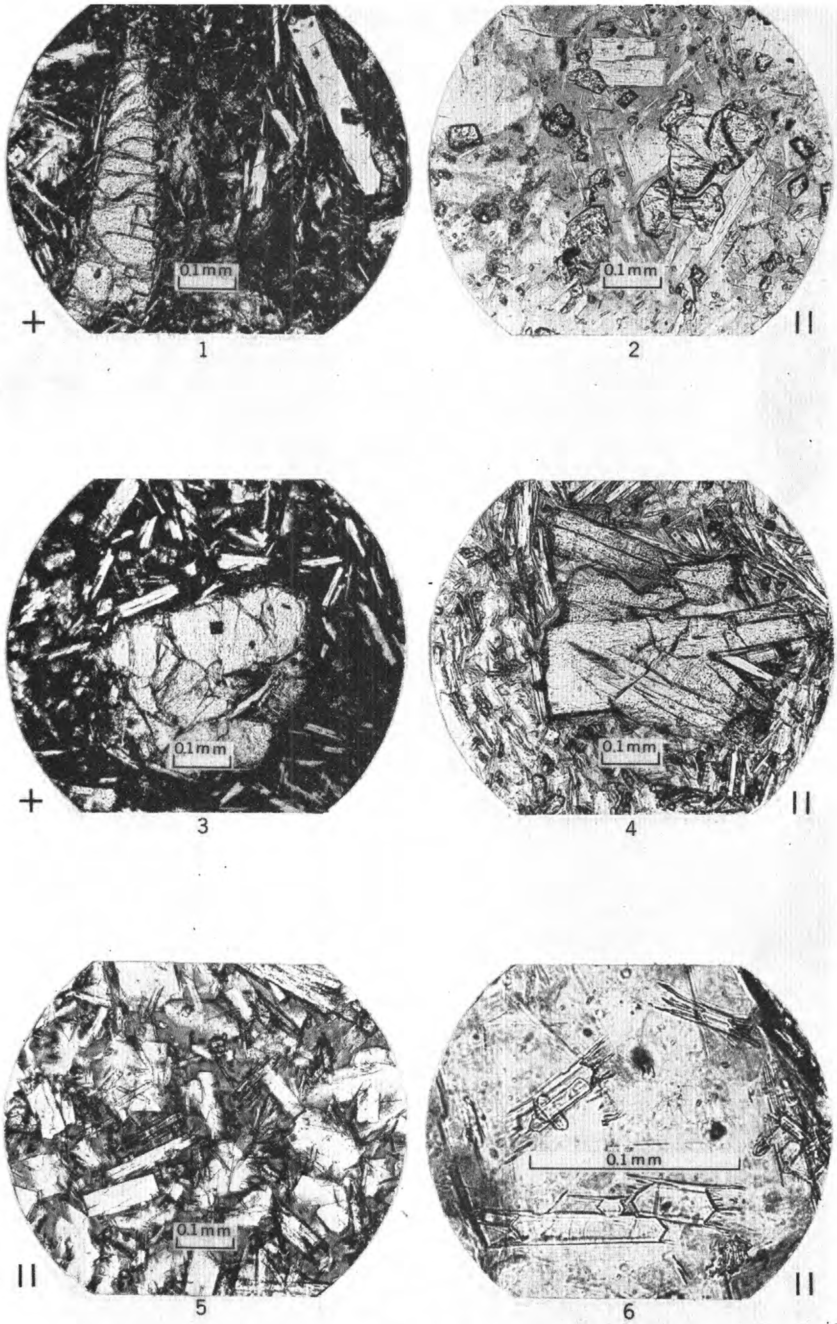
2. Pumice fragment erupted April 1944 (Instituto de Geología de México), thin section showing microphenocrysts of olivine and plagioclase and microlites of olivine and clinopyroxene (rods) in clear glass. Plane polarized light.

3. Lava erupted April 9, 1947 (analysis 12, table 2), showing olivine megaphenocryst with thin reaction rim of fine-grained orthopyroxene. Crossed nicols.

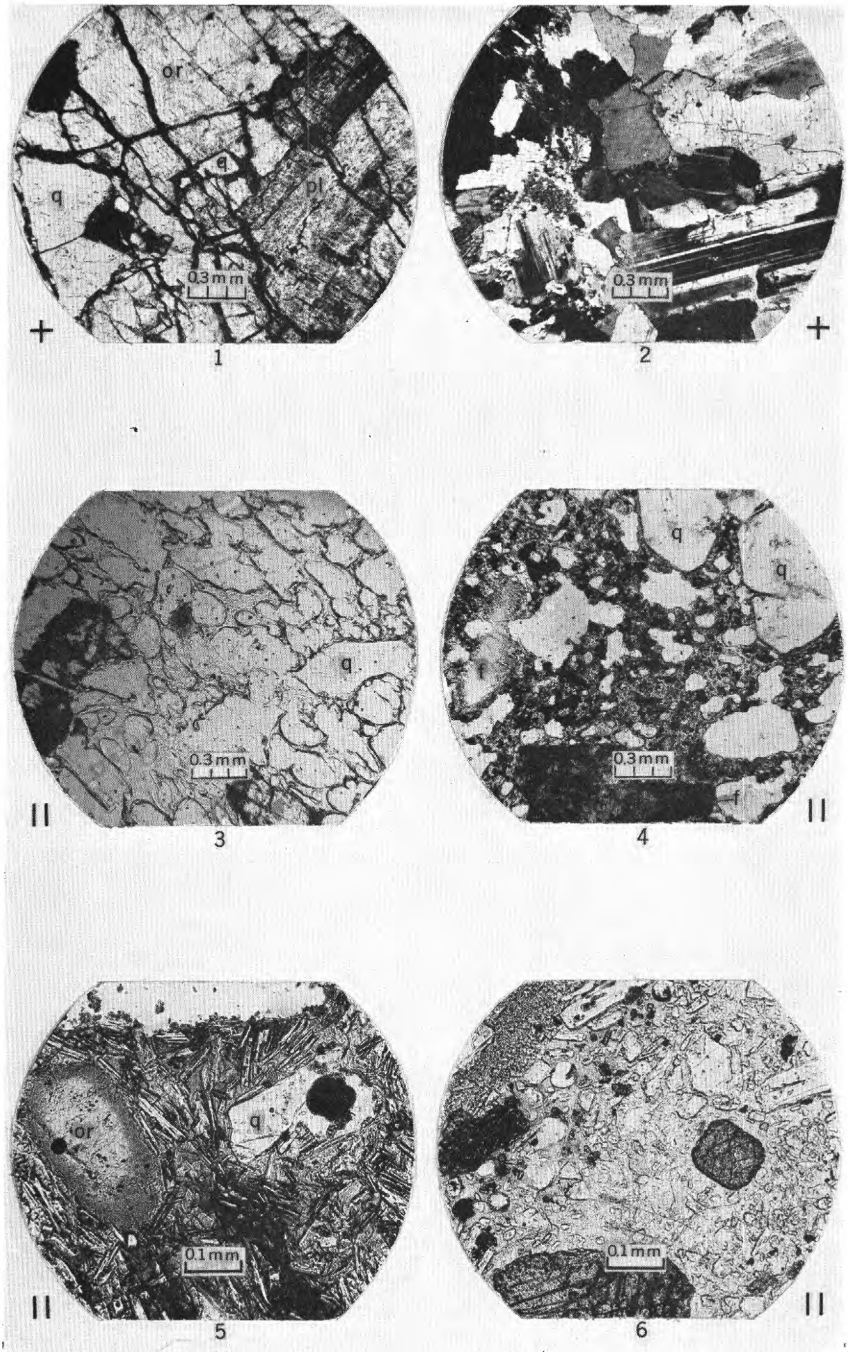
4. Lava erupted September 1950 (analysis 19, table 2), showing orthopyroxene megaphenocryst cluster. Plane polarized light.

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.



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 $X' \wedge 010$ 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}).

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 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 $X'\wedge 010_{max}=33°–38°$ (An_{56-66}) and $X'\wedge 010 \perp a=32°–36°$ (An_{60-70}). Refractive index on cleavage, $nX'=1.562$, implying compositions about 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° (An_{56}) in some crystals. Orthopyroxene microphenocrysts have (negative) $2V=75°–78°$, implying compositions of 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

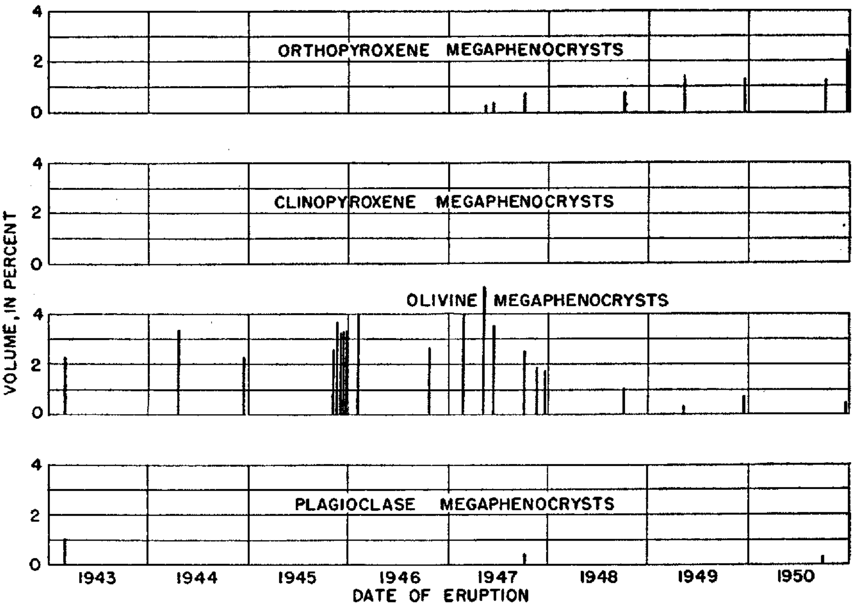


FIGURE 98.—Volume percentages of megaphenocrysts in some Parícutin ejecta, plotted according to date of eruption.

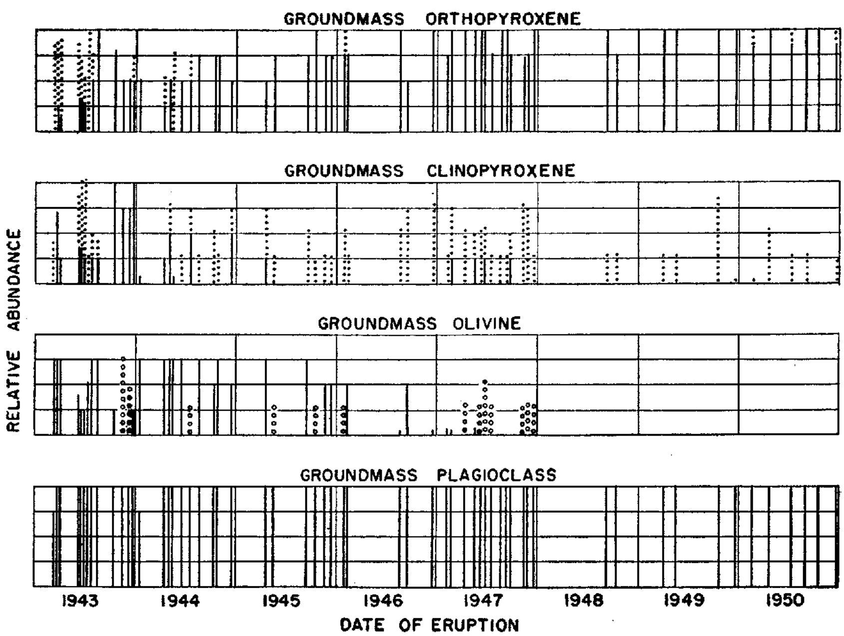


FIGURE 99.—Relative abundances of groundmass minerals in Parícutin ejecta, plotted according to date of eruption. Microphenocrysts are shown by solid bars, reacting olivine by circle bars, and microlites by dotted bars.

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_5 (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

285997—54——5

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.

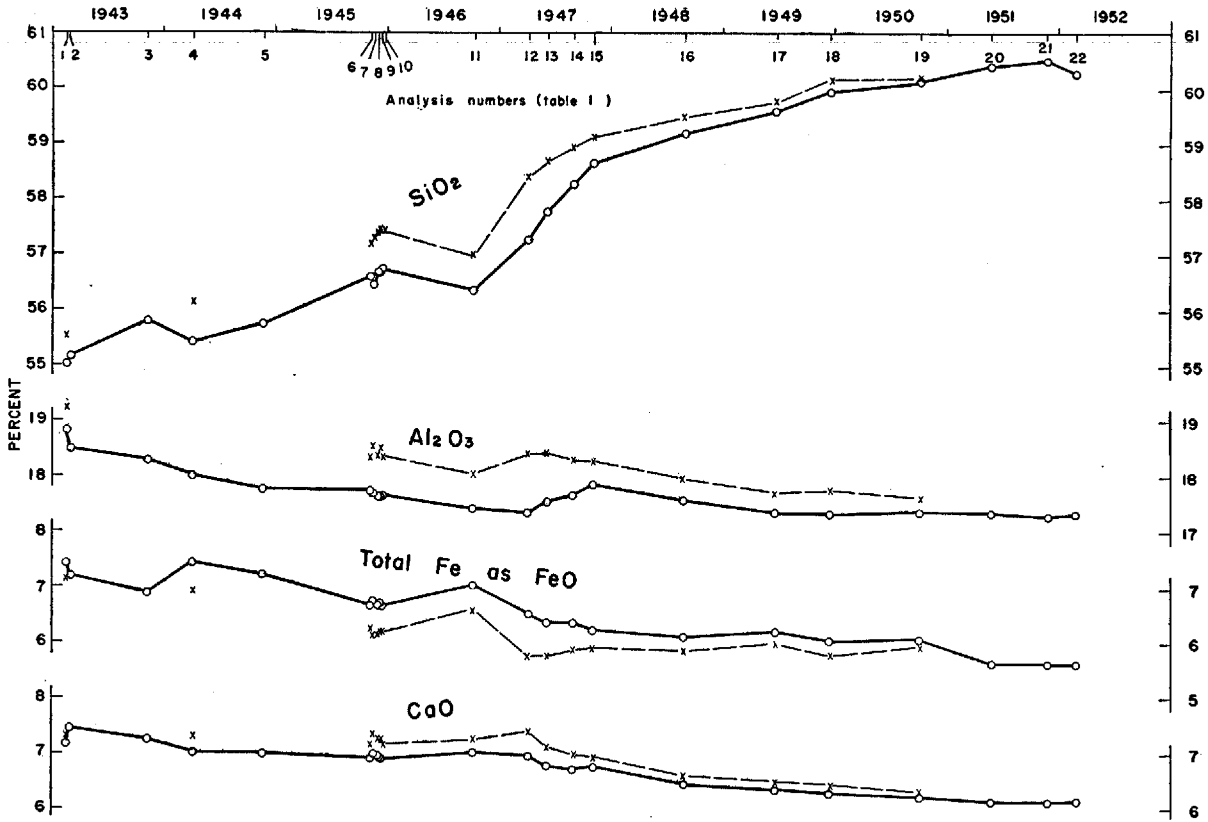
The resulting graph of figure 100 shows in a striking manner that the oxide constituent of successively erupted lavas have varied serially during the course of the eruption. Silica increased from about 55 percent in 1943 to slightly over 60 percent in 1952; potash increased consistently if only a small 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
Analysis numbers (table 1)
SiO2
Al2 O3
Total Fe as FeO
CaO
PERCENT

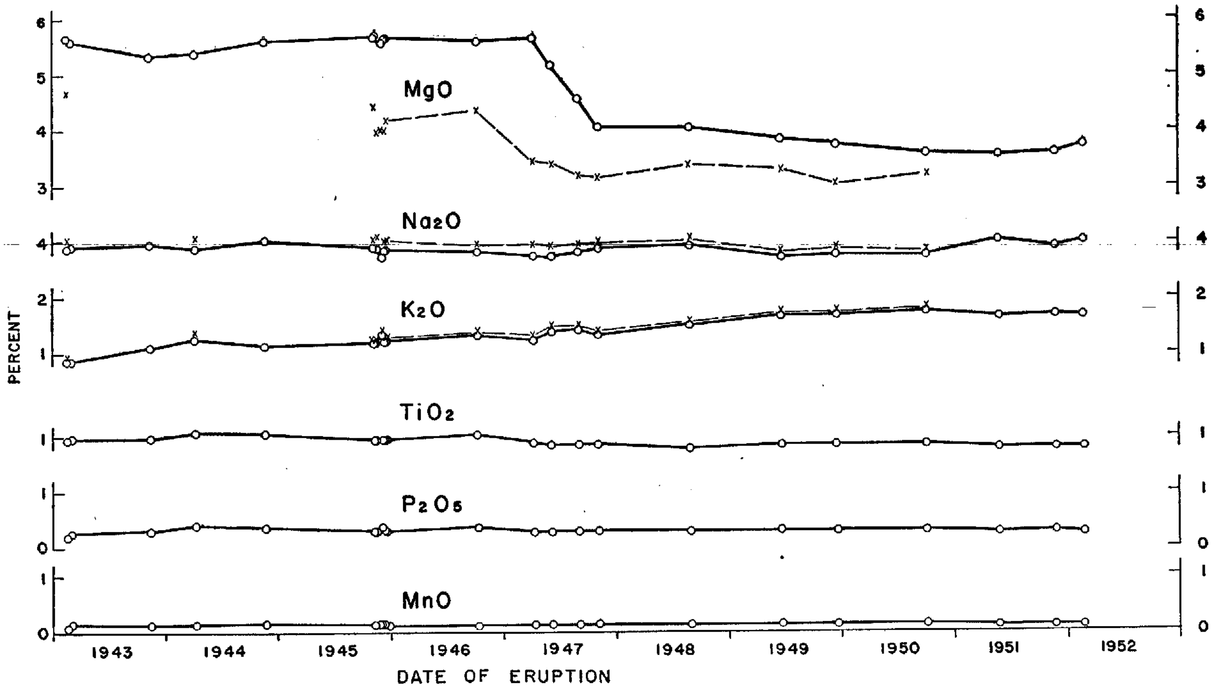


FIGURE 100.—Compositions of lavas of Parícutin volcano, plotted according to date of eruption. Bulk analyses (table 2), recast with all iron as FeO and excluding volatiles, are plotted as circles. Calculated groundmass compositions (table 2) are plotted as crosses.

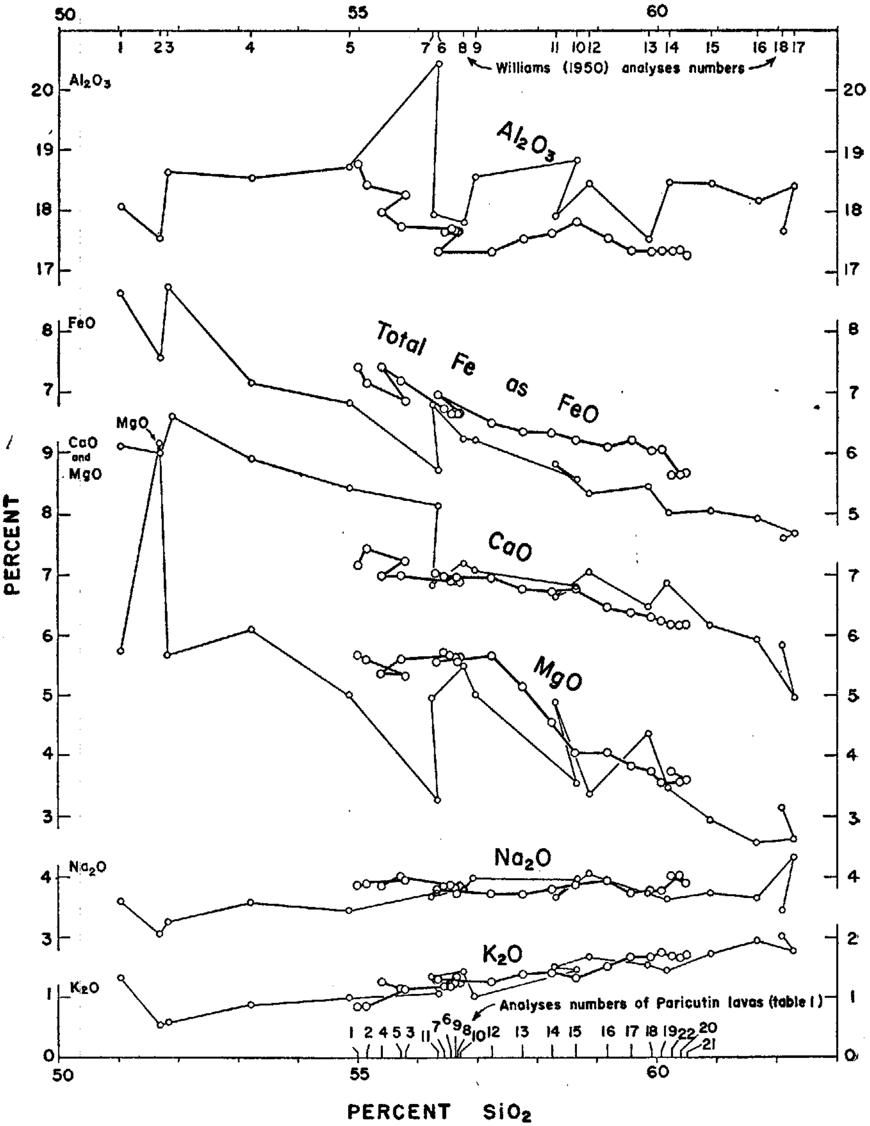


FIGURE 101.—Silica-variation diagram of lavas of Parícutin and nearby volcanoes. Large circles show lavas of Parícutin connected in order of eruption. Small circles show lavas of nearby volcanoes connected in order of analysis number (Williams, 1950, table 1). Both sets of analyses have been recast with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

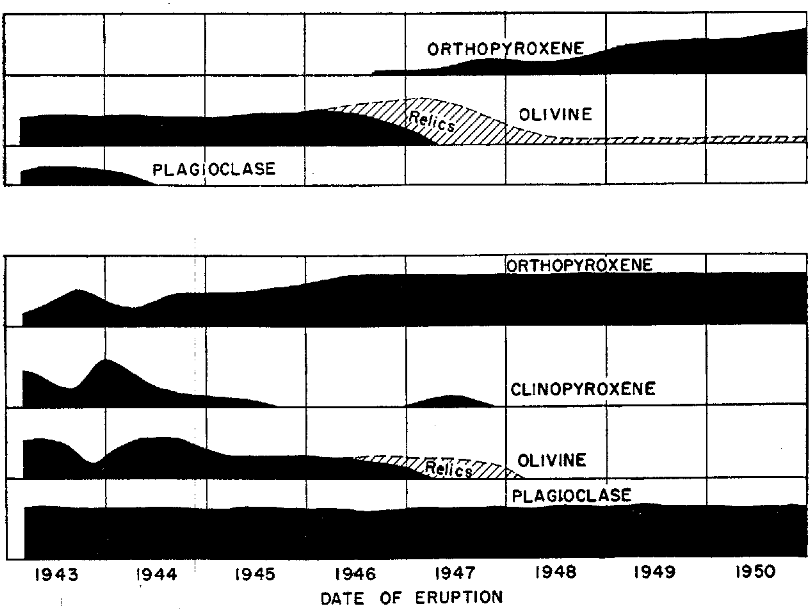


FIGURE 102.—Occurrence of megaphenocrysts (upper) and microphenocrysts (lower) in successive Parícutin ejecta of 1943 to 1950 (generalized from data of figures 98 and 99).

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

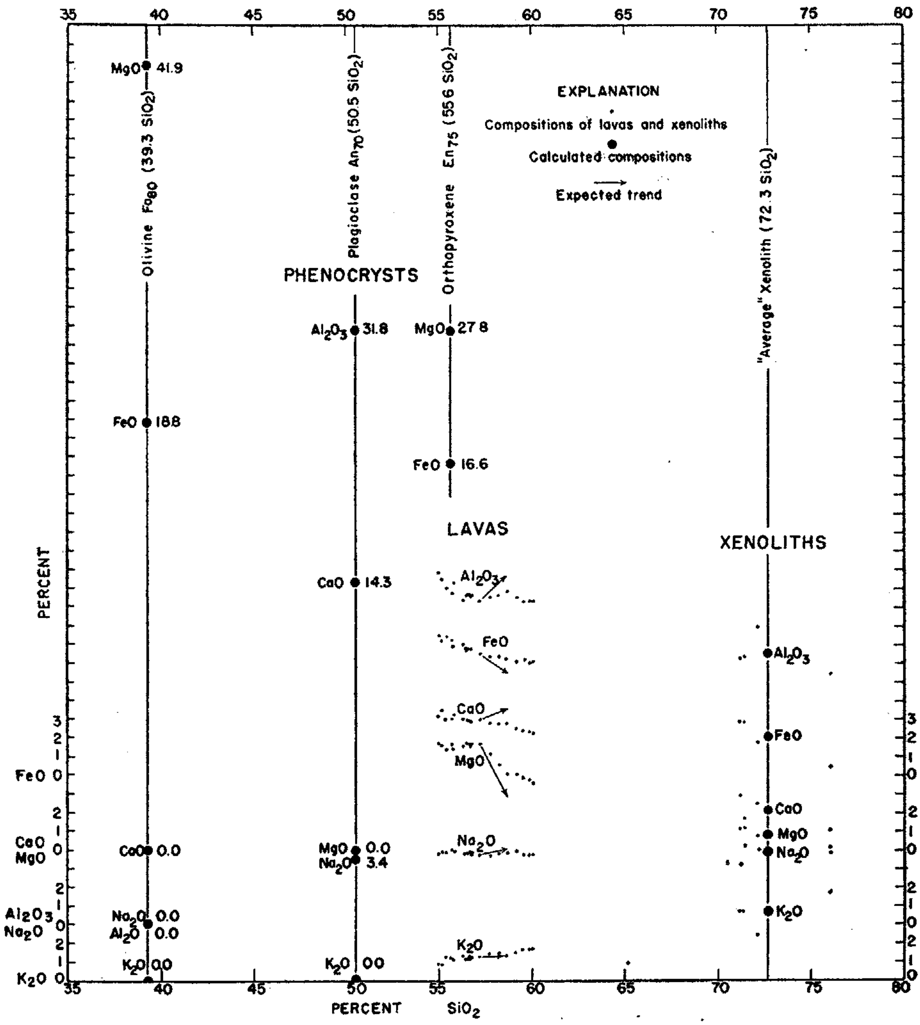


FIGURE 103.—Silica-variation diagrams of lavas, phenocrysts, and xenoliths of Parícutin volcano. Dots represent bulk compositions of lavas and xenoliths (analyses 6–10 averaged). Values for bulk compositions are counted from 0 point for each oxide at bottom of scale. Arrows from analysis 13 show trends 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.

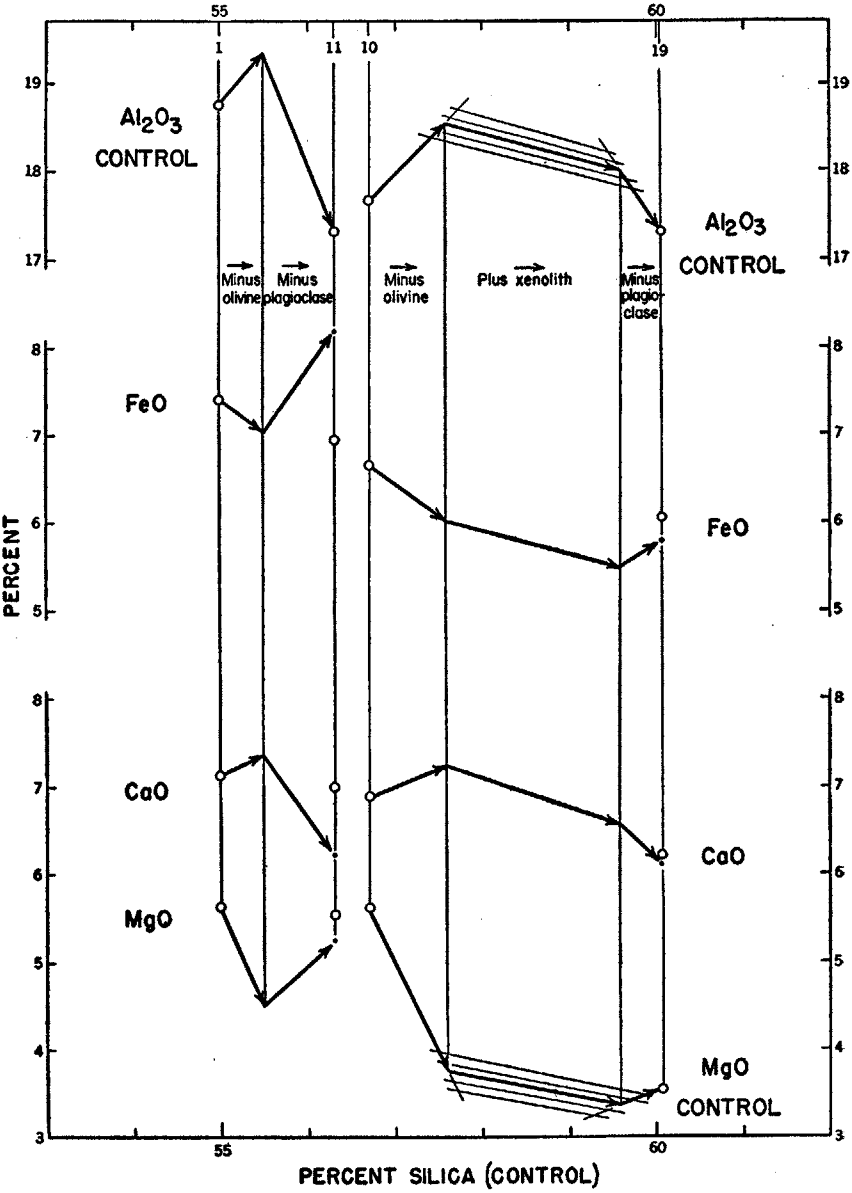


FIGURE 104.—Silica-variation diagrams, showing graphical operations in addition and subtraction of materials from bulk compositions (represented by open circles) of lavas of Parícutin volcano. Dots opposite FeO, CaO, and MgO of no. 11 show percentages in final product subtracting olivine, Fo_{80}, and plagioclase, An_{78}, 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-

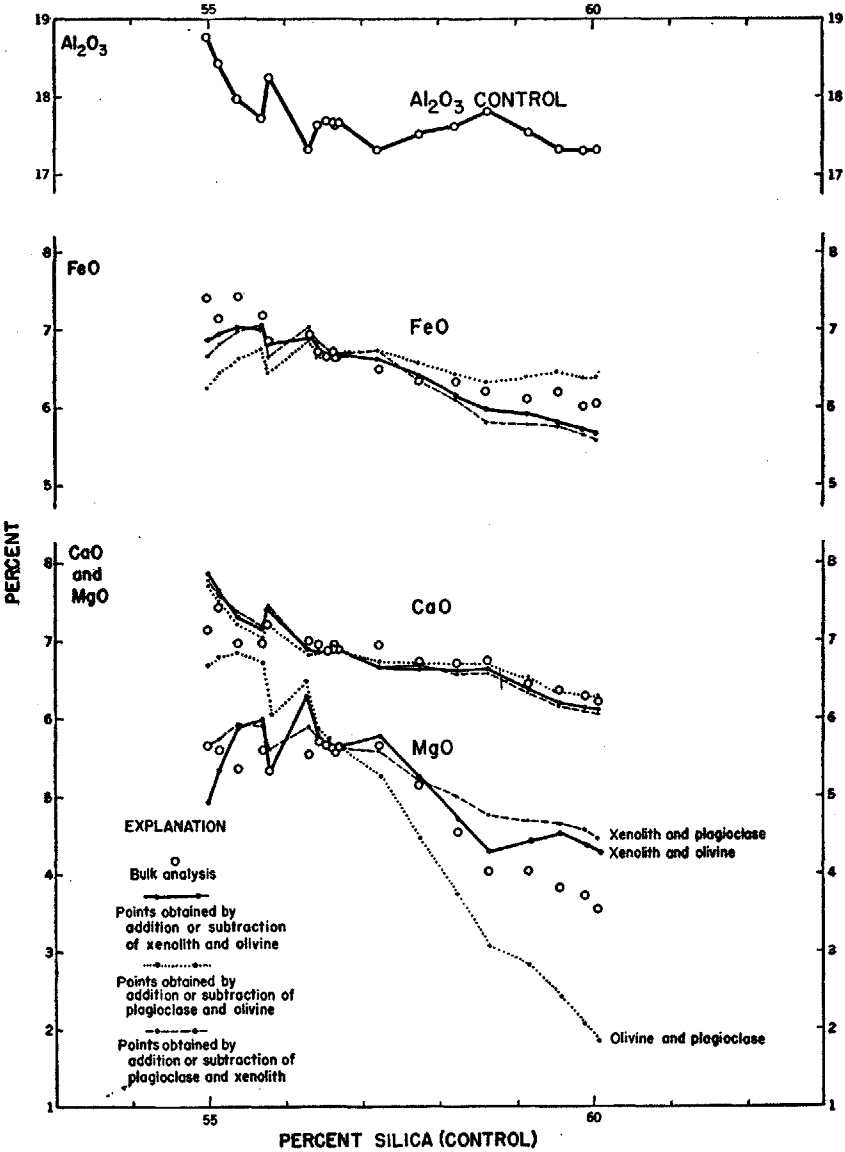


FIGURE 105.—Silica-variation diagram comparing actual bulk compositions (open circles) with trends developed by graphical addition or subtraction of olivine, plagioclase, and xenolithic material two at a time, from analysis 10 (tables 2 and 3), using SiO_2 and Al_2O_3 as controls. Dotted lines connect 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}.

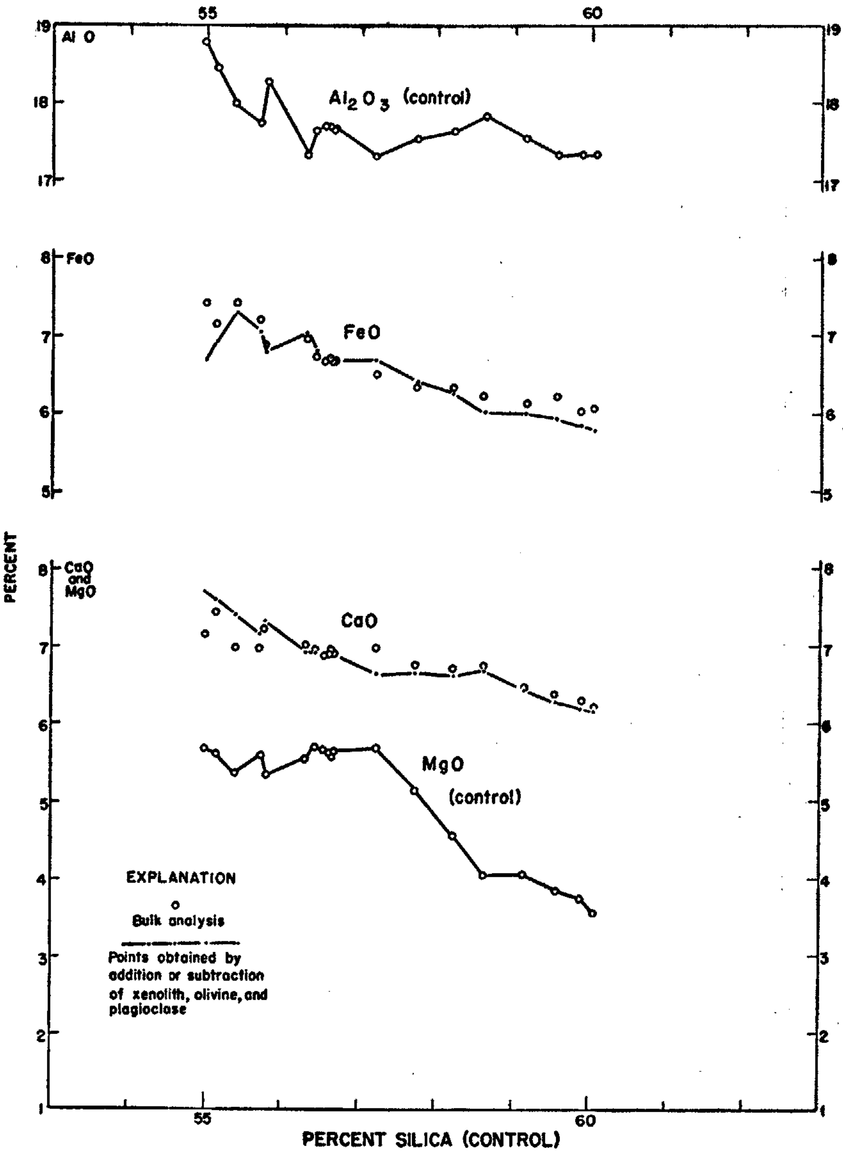


FIGURE 106.—Silica-variation diagram comparing actual bulk compositions of Parícutin lavas (open circles) with trends developed by graphical addition or subtraction of olivine, plagioclase, and xenolithic material from analysis 10 (table 2), using SiO_2, Al_2O_3, and MgO as controls.

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	to left	to right	to left	to right	to left	to right	to left	to right	over-all
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

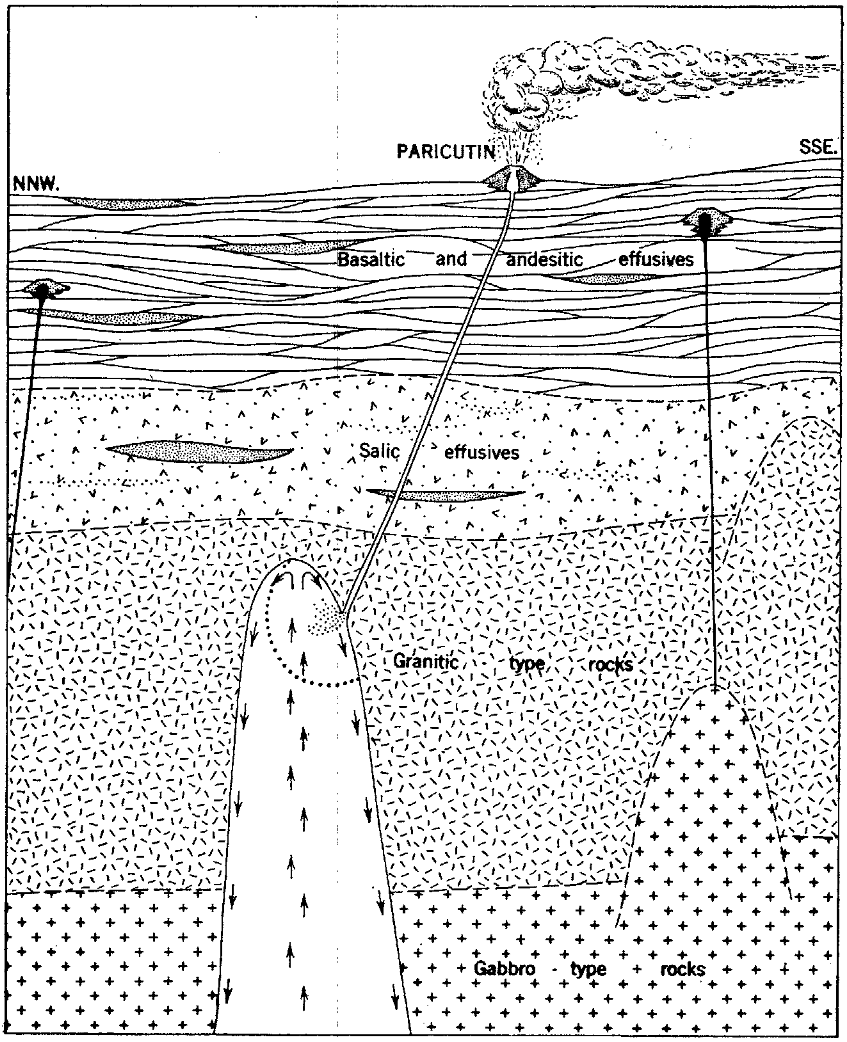


FIGURE 107.—Schematic cross section of Parícutin volcano and its supposed magma cupola. Arrows represent character of slow thermal convection. Area within dotted line represents cross section of approximate volume of magma erupted during 1943–52. Depth of top of gabbroic-type rocks assumed to be about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

LITERATURE CITED

Bowen, N. L., 1928, The evolution of the igneous rocks: Princeton, p. 1–334.

Chayes, F., 1949, A simple point counter for thin-section analysis: Am. Min., v. 34, p. 1–11.

Daly, R. A., 1914, Igneous rocks and their origin: New York, p. 1–563.

——— 1933, Igneous rocks and the depths of the earth: New York, p. 1–598.

Foshag, W. H., and González R., J., 1954 (in preparation), U. S. Geol. Survey Bull, 965–D.

Fries, C., Jr., 1953, Volumes and weights of pyroclastic material, lava and water erupted by Parícutin Volcano, Michoacán, Mexico: Am. Geophys. Union Trans., v. 34, p. 603–616.

Fries, C., Jr., and Gutiérrez, C., 1950a, Activity of Parícutin Volcano from August 1, 1948, to June 30, 1949: Am. Geophys. Union Trans. v. 31, p. 406–418.

——— 1950b, Activity of Parícutin Volcano from July 1 to December 31, 1949: Am. Geophys. Union Trans., v. 31, p. 732–740.

——— 1951a, Activity of Parícutin Volcano from January 1 to June 30, 1950: Am. Geophys. Union Trans., v. 32, p. 212–221.

——— 1951b, Activity of Parícutin Volcano from July 1 to December 31, 1950: Am. Geophys. Union Trans., v. 32, p. 572–581.

——— 1952a, Activity of Parícutin Volcano from January 1 to June 30, 1951: Am. Geophys. Union Trans., v. 33, p. 91–100.

Fries, C., Jr., and Gutiérrez, C., 1952b, Activity of Parícutin Volcano from July 1 to December 31, 1951: Am. Geophys. Union Trans., v. 33, p. 725–733.

——— 1954, Activity of Parícutin Volcano during 1952: Am. Geophys. Union Trans. v. 35.

González R., J., and Foshag, W. H., 1947, The birth of Parícutin: Smithsonian Inst. Ann. Rept. for 1946, Washington, D. C., p. 223–234.

Goranson, R. W., 1942, Heat capacity; heat of fusion, (*in* F. Birch, J. F. Schairer, and H. C. Spicer: Handbook of Physical Constants): Geol. Soc. America Special Paper no. 36, p. 223–242.

Harker, A., 1900, Igneous rock-series and mixed igneous rocks: Jour. Geology, v. 8, p. 389–399.

——— 1909, The natural history of igneous rocks: New York p. 1–384.

Hess, H. H., and Phillips, A. H., 1940, Optical properties and chemical composition of magnesian orthopyroxenes: Am. Mineralogist, v. 25, p. 271–285.

Holmes, A., 1931, The problem of the association of acid and basic rocks in central complexes: Geol. Mag., v. 68, p. 241–255.

Johannsen, A., 1937, A descriptive petrography of the igneous rocks: v. 3, The intermediate rocks: Chicago, p. 1–361.

Kennedy, G. C., 1946, Activity of Parícutin Volcano from April 12 to May 3, 1946: Am. Geophys. Union Trans., v. 27, p. 410–411.

——— 1947, Charts for correlation of optical properties with chemical composition of some common rock-forming minerals: Am. Mineralogist, v. 32, p. 561–573.

Köhler, A., 1949, Recent results of investigations on the feldspars: Jour. Geology, v. 57, p. 592–599.

Krauskopf, K. B., 1948a, Mechanism of eruption at Parícutin Volcano, Mexico: Geol. Soc. America Bull., v. 59, p. 711–731.

——— 1948b, Lava movement at Parícutin Volcano, Mexico: Geol. Soc. America Bull., v. 59, p. 1267–1284.

Krauskopf, K. B., and Williams, H., 1946, The activity of Parícutin Volcano during its third year: Am. Geophys. Union Trans., v. 27, p. 406–410.

Kuno, H., 1950, Petrology of Hakone Volcano and the adjacent areas, Japan: Geol. Soc. America Bull., v. 61, p. 957–1019.

Larsen, E. S., Jr., 1938, Some new variation diagrams for groups of igneous rocks: Jour. Geology, v. 46, p. 505–520.

Larsen, E. S., Jr., and Switzer, G., 1939, An obsidian-like rock formed from the melting of a granodiorite: Am. Jour. Sci., v. 237, p. 562–568.

Larsson, W., 1941, Petrology of interglacial volcanics from the Andes of northern Patagonia: Upsala Univ. Geol. Inst. Bull., v. 28, p. 191–405.

Milton, C., 1945, Notes on volcanic rocks from Parícutin, Mexico: Am. Geophys. Union Trans., v. 25, p. 618–621.

Morey, G. W., and Bowen, N. L., 1922, The melting of potash feldspar: Am. Jour. Sci., 5th ser., v. 4, p. 1–21.

Niggli, P., and Beger, P. J., 1923, Gesteins- und Mineralprovinzen, I: Berlin, p. 1–602.

Ordóñez, Ezequiel, 1947, El Volcan de Parícutin: Editorial Fantasia, Mixcoac, D. F., p. 1–181.

Peacock, M. A., 1931, Classification of igneous rock series: Jour. Geology, v. 39, p. 54–67.

Poldervaart, A., and Hess, H. H., 1951, Pyroxenes in the crystallization of basaltic magma: Jour. Geology, v. 59, p. 472–489.

Rittmann, A., 1929, Die Zonenmethode: Schweizer. min. pet. Mitt., Band 9, p. 1–46.

Rosenfeld, J. L., 1950, Determination of all principal indices of refraction on difficultly oriented minerals by direct measurement: Am. Mineralogist, v. 35, p. 902–905.

Schmitter, Eduardo, 1945, Estudia petrográficò de lavas y productos piroclasticos; determinación de las formas cristalinas e indices de refracción de algunos de los sublimados del volcán, *in* El Parícutin: Inst. geol. México, Univ. Nac. Autonoma, p. 111–131.

Segerstrom, K., 1950, Erosion studies at Parícutin Volcano, State of Michoacán, Mexico: U. S. Geol. Survey Bull. 965–A, p. 1–164.

Tröger, W. E., 1952, Tabellen zur optischen Bestimmung der gesteinbildenen Minerale: Stuttgart, p. 1–147.

Wilcox, R. E., 1944, Rhyolite-basalt complex on Gardiner River, Yellowstone Park, Wyoming: Geol. Soc. America Bull., v. 55, p. 1047–1079.

——— 1947a, Activity of Parícutin Volcano from September 18 to November 30, 1946: Am. Geophys. Union Trans., v. 28, p. 567–572.

——— 1947b, Activity of Parícutin Volcano from December 1, 1946, to March 31, 1947: Am. Geophys. Union Trans., v. 28, p. 725–731.

——— 1948a, Activity of Parícutin Volcano from April 1 to July 31, 1947: Am. Geophys. Union Trans., v. 29, p. 69–74.

——— 1948b, Activity of Parícutin Volcano from December 1, 1947 to March 31, 1948: Am Geophys. Union Trans., v. 29, p. 355–360.

Wilcox, R. E., and Gutiérrez, C., 1948, Activity of Parícutin Volcano from April 1 to July 31, 1948: Am. Geophys. Union Trans., v. 29, p. 877–881.

Wilcox, R. E., and Shoup O., S., 1948, Activity of Parícutin Volcano from August 1 to November 30, 1947: Am. Geophys. Union Trans., v. 29, p. 74–79.

Williams, H., 1950, Volcanoes of the Parícutin region: U. S. Geol. Survey Bull. 965–B, p. 165–279.

Winchell, A. N., 1951, Elements of optical mineralogy: Part 2, 4th edition, p. 1–551, New York.

Zies, E. G., 1946, Temperature measurements at Parícutin Volcano: Am. Geophys. Union Trans., v. 27, p. 178–180.

INDEX

Birth and Development of Parícutin Volcano Mexico

By WILLIAM F. FOSHAG *and* JENARO GONZÁLEZ R.

GEOLOGIC INVESTIGATIONS IN THE PARÍCUTIN AREA, MEXICO

G E O L O G I C A L   S U R V E Y   B U L L E T I N   9 6 5 – D

Prepared in cooperation with the Comisión Impulsora y Coordinadora de la Investigación Científica de México, under the auspices of the Interdepartmental Committee on Scientific and Cultural Cooperation, Department of State

---

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1956

UNITED STATES DEPARTMENT OF THE INTERIOR

Douglas McKay, *Secretary*

GEOLOGICAL SURVEY

W. E. Wrather, *Director*

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C.

CONTENTS

ILLUSTRATIONS

[Plates 12-15 are in pocket; plates 16-51 follow index]

TABLES

GEOLOGIC INVESTIGATIONS IN THE PARÍCUTIN AREA, MEXICO

BIRTH AND DEVELOPMENT OF PARÍCUTIN VOLCANO

By William F. Foshag[1] and Jenaro González R.

ABSTRACT

The Michoacán volcanic province is a portion of the Mexican Volcanic Axis, a zone of major volcanism that lies between parallels 19° and 20° and extends from the Pacific littoral to the gulf coast. The Michoacán province includes numerous basaltic and andesitic volcanic cones and flows of Pliocene, Pleistocene, and Recent age. The newest addition to these volcanic edifices broke forth from cultivated fields near the village of Parícutin on February 20, 1943, and has been named Parícutin volcano.

The first manifestations of new volcanic activity in the region were local seisms and subterranean noises that became apparent 2 weeks before the actual outbreak of volcanic eruption. These seisms increased in number and intensity until February 20, when the first volcanic outbreak occurred and the seisms ceased.

At about 4:30 p. m. of this day four eyewitnesses observed a mild explosion at a newly formed fissure in the fields of Llano de Cuiyúsuru, a farm lying 2 kilometers southeast of Parícutin village. A small eruptive column carrying dust and some hot stones arose from this new vent. For several hours the vent increased in size by the slumping of its walls, and the eruptive column grew in size. After about 8 hours of such activity the new volcano began to roar and to hurl out quantities of incandescent bombs with great force.

The new cone grew with great rapidity, reaching a height of 167 meters in 6 days of activity.

The volcanic activity of Parícutin during the initial period of 2½ years can be divided into three periods: (1) Quitzocho period, during which the activity was centered about the original Cuiyúsuru vents and during which the volcano built its cone; (2) Sapichu period, with the principal activity taking place in the later Sapichu vents and the adventitious cone, Sapichu; and (3) Taquí period, when activity was largely connected with the Taquí and Ahuán vents.

The early part of the Quitzocho period was devoted to the building of the cone. Several recurrent surges of lava breached the growing cone. These breaches were rapidly repaired with each cessation of lava flow. The early ejectamenta was largely bombs and lapilli; after 1 month's activity the crater yielded largely cineritic material. During the latter part of the Quitzocho period, activity was more erratic and variable; a number of lava flows connected with the original vents broke from the flanks of the new cone and partially breached its walls. Flows spread over the fields to the north of the volcano, and explosive activity in the crater sometimes reached tremendous proportions.

During the Sapichu period activity shifted to a series of new vents at the northeast base of the cone. An adventitious cone, called Sapichu, formed; and a lava

[1] Published by permission of the Secretary of the Smithsonian Institution.

flow, the Sapichu flow, covered the fields to the northeast. During the eruption of Sapichu the activity of the main cone was greatly reduced.

With cessation of activity at Sapichu, the main crater renewed its activity, and lava issued alternately from vents on the west and south base of the cone, the Taquí and Ahuán vents respectively. Lava flowed from one or the other vent almost continuously, but eruptive activity in the crater was erratic and variable and showed no apparent correlation with the emission of lava. When the lava flowed beneath a congealed crust, hornitos and volcancitos resulted.

After 3 years of activity the cone of Parícutin had reached a height of about 350 meters above the original vent. The altitude of the original vent, although never measured, was calculated from the elevation of the Parícutin–Uruapan road and an estimated slope of the terrain of about 5° as 2,400 meters. Later, the increment of ash added to the cone was largely balanced by rainwash and slumping. The lava flows covered an area of about 18½ square kilometers and destroyed the villages of Parícutin and San Juan Parangaricutiro.

The lavas of Parícutin, during the first 2½ years of its life, were andesite-basalt and showed little variation during that period.

INTRODUCTION

PREVIOUS INVESTIGATIONS

Numerous accounts of the activity of Parícutin volcano have appeared, most of which impart the impression of the visitor during a very brief observation. A complete list has been compiled by Robert T. Hatt (1950). The first geological visitor to the scene was Ing. Ezequiel Ordóñez (1943, 1945, 1947), who has given us various detailed accounts of the volcano's activity. Other early accounts are given by Waitz (1943), De la O Carreño (1943), Robles Ramos (1943), Trask (1943), and others. A series of papers concerning Parícutin, published under the title El Parícutin, contains a description of the early activity (Flores and others, 1945). The events connected with the initial outbreak have been described by González and Foshag (1947), basing their narrative upon eyewitness accounts. White (1945) and Bullard (1947) have contributed details covering brief periods in the volcano's history.

The area around Parícutin was mapped and described by Williams (1950), and the region lying between the Parícutin area, the Balsas River, and the Pacific coast was described and mapped by González and Pérez-Siliceo (unpublished). Erosion studies have been made by Segerstrom (1950).

FIELDWORK

At the time of the initial outbreak of Parícutin volcano, we were engaged in surveys relating to the mineral resources of Mexico. The duties incident to this task allowed us only occasional opportunity to visit the new volcano. It was not our original intention to compile a history of the volcano's activity, but it soon became apparent that our notes and observations contained data of unusual interest. We

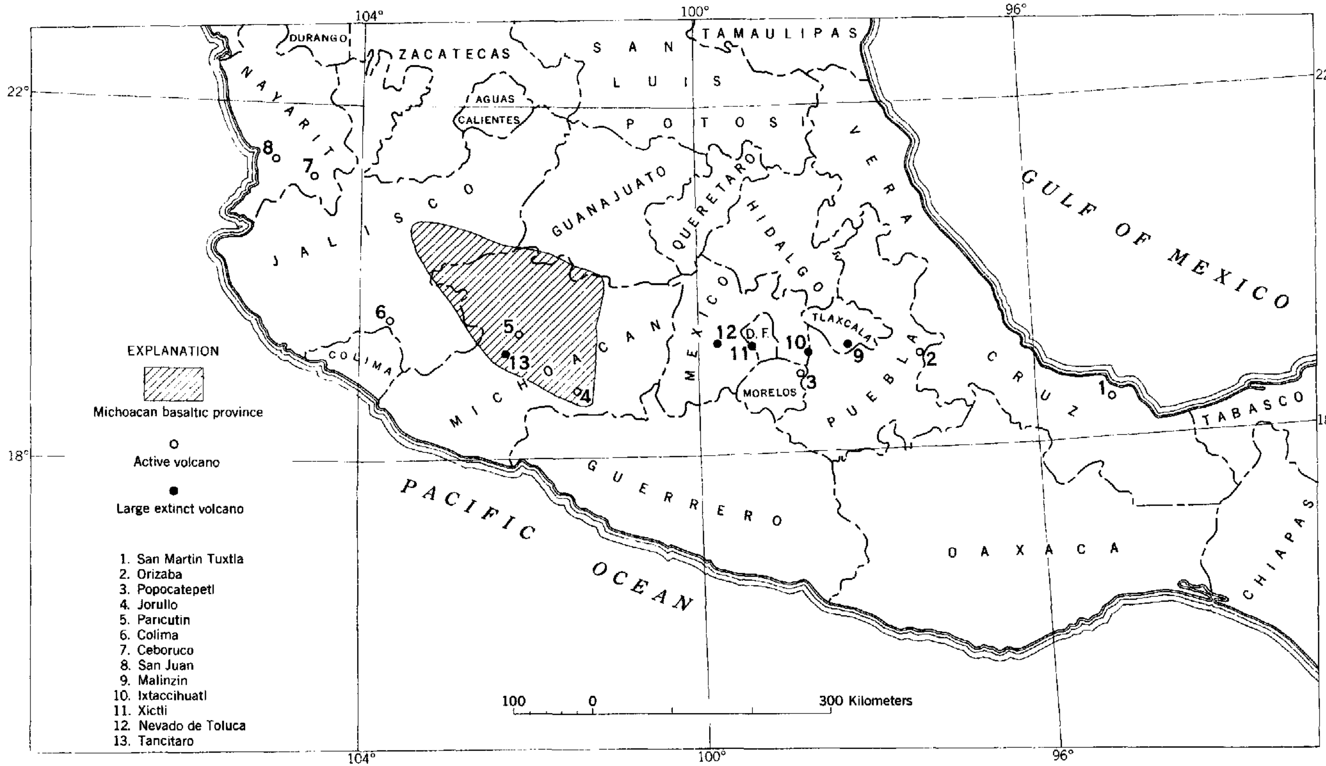


FIGURE 108.—Index map of southern Mexico, showing the Mexican Volcanic Axis.

were particularly fortunate in being present during most of the important phases or at the time of critical changes in activity during the period covered in this report. Our observations have been supplemented, wherever necessary, by notes or information furnished by other visiting geologists. Proper acknowledgment for these data are included in the body of the narrative.

Our base was principally a small cabin we built on Cerro de Jarátiro [2] a kilometer from the base of the new cone. Later we occupied a more commodious cabin built by the Instituto de Geología on the same hill. This point offered an excellent panoramic view, particularly since the early activity took place immediately in front of the hill. During the early phases of the volcano's activity, the area covered by lava was so small that one-half hour's walk took one to any sector of activity, or one could easily circle the entire area in a few hours of leisurely wandering. Consequently, few events escaped our notice.

The periods of observation, together with the names of the Mexican or American geologists present, other than W. F. Foshag, who was present on all dates noted, were as follows:

1943	
Mar. 25–26	Ezequiel Ordóñez, Donald White.
May 21–26	Frederick Pough.
June 9–18	Frederick Pough, G. A. Cooper, Adán Pérez-Peña.
July 16–19	Donald White.
July 24–Aug. 3	Jenaro González R., Carl Fries, Jr.
Sept. 16–17	James MacAllister, David Gallagher.
Nov. 28–Dec. 7	Adán Pérez-Peña.
1944	
Jan. 8–11	Jenaro González R., Ezequiel Ordóñez.
Feb. 10–13	Jenaro González R., Eduardo Schmitter.
Mar. 1–4	David Larrabee.
Mar. 21–24	Jenaro González R.
Apr. 5–6	Jenaro González R.
Apr. 24–25	Jenaro González R.
May 22–25	Ezequiel Ordóñez, Ward Smith, David Gallagher.
June 29–July 1	Jenaro González R.
July 6–8	Jenaro González R.
Aug. 14–18	Richard Fuller.
Sept. 16–18	Edwin Eckel, James MacAllister, David Gallagher.
Nov. 24–Dec. 8	Ezequiel Ordóñez, E. Zies, Howel Williams, F. G. Wells.

[2] The authors prefer the spelling Arátiro, following Gilberti, Diccionaria de la lengua Tarasca, and the rules of Tarascan grammar formulated by Najera, Gramatica de la lengua Tarasca, but for the sake of consistency have agreed to follow the spelling used in previous chapters of this bulletin.

1945

Jan. 16–25	Jenaro González R., Howel Williams.
May 27–29	Carl Fries, Jr., J. V. N. Dorr 3d.
July 3–5	Ezequiel Ordóñez, William Wrather, Carl Fries, Jr.
July 24–31	Jenaro González R.
Aug. 6	Jenaro González R., Enrique Cantero.

In this report the authors have attempted to present a strictly factual account of the birth and development of Parícutin volcano and avoid any interpretive opinions that might break the true narrative of events.

ACKNOWLEDGMENTS

The observations contained in this report were made whenever time could be spared from a cooperative program of the Instituto de Geologia, the Comité Directivo para la Investigacion de los Recursos Minerales de México, the U. S. Geological Survey, and the Smithsonian Institution, under the auspices of the Interdepartmental Committee on Scientific and Cultural Cooperation, United States Department of State. This project had, for its primary object, the study of important mineral resources in Mexico. The program, of which these Parícutin volcano studies became an incidental part, was supervised by Ing. Teodoro Flores, Acting Director of the Instituto de Geología; Ing. Ezequiel Ordóñez, member, Comité Directivo; Mr. John V. N. Dorr 3d, United States Geological Survey; and Dr. A. Wetmore, Smithsonian Institution. Realizing the unusual nature of this rare manifestation, they gave ready consent and encouragement to this project; and for these, and their many other contributions, we are deeply grateful.

The friendly villagers of San Juan Parangaricutiro and Parícutin gave us much assistance. We are particularly indebted to the late Sr. Felipe Cuara Amezcua, Presidente of the Municipio of San Juan Parangaricutiro, for many courtesies and valuable help, as well as for his solicitous attention to our well-being while at our isolated and exposed camp; and to our helpers, Celedonio Gutiérrez and Luis Aguilar, for faithful service under difficult and sometimes dangerous conditions. For their accounts of the initial outbreak of the volcano and the events of the first day we are greatly indebted to the following persons: Sr. Dionisio Pulido, his wife, Paula, and his brother, Dolores Pulido, of Parícutin (now of Caltzontzin), and Sra. Aurora Cuara, Srs. Luis Ortíz Solorio, Jesús Anguiano Espinosa and Jesús Martinez of San Juan Parangaricutiro (now of Ahuanicutiro), and Sr. José Caballero, now of Cherán.

Many visiting geologists have furnished us with information concerning the activity of the volcano during their stay. We are particularly indebted to Mr. Donald White, of the United States Geological Survey, for copies of his notes for the periods July 16–19 and October 1–5, 1943, and February 4–6, 1944, and to Sr. Adán Pérez-Peña for copies of his notes for the period June 9–19, 1943. Sr. Pérez-Peña also mapped, at our request, the lavas of 1943.

One of the important tasks we set to do was the collecting of significant photographs depicting the development of the volcano. Proper credit is given for each contribution of photographs used in this report. Unless otherwise noted, photographs are by W. F. Foshag. We are particularly grateful to Dr. O. O. Fisher for his efforts in this project. Many of the early photographs were assembled through his efforts. We are likewise indebted to Dr. Frederick H. Pough, of the American Museum of Natural History, for copies of striking color motion pictures of the activity of the volcano.

The keen interest of Dr. O. O. Fisher in the project again manifested inself in funds for the rebuilding of the cabin observatory on Cerro de Jarátiro when lava flows were about to destroy it, for supplies for our comfort, and for the use of his private airplane for observations about the volcano. We are likewise indebted to Col. Ray Baker for the use of his plane for similar purposes.

The drawings for figures 111–123 included in this report are the work of William Crockett, artist, Department of Geology, United States National Museum.

Funds for the chemical analyses of early lavas and bombs were appropriated by the United States Committee for the Study of Parícutin volcano, from a grant of the Geological Society of America.

EARLY LAVAS

The lavas that flowed from the Parícutin vents during its early formative period were basaltic in nature and aa or block lava in character. Samples of all the flows during this period were collected, and the analysis of four appears in table 1. These four samples represent (1) the first lava, the Quitzocho flow, March 5, 1943; (2) the Sapichu lava, which issued during the period October–November 1943, collected at its front near the San Juan Parangaricutiro–Uruapan road on April 24, 1944; (3) the Ahuán flow, which opened in mid-November 1944, collected at the lava vent on December 2, 1944; and (4) the Taquí flow, which began on January 8, 1943, sample collected from active lava flow at the base of Cerro de Jarátiro on July 27, 1945.

A very slight progression toward a more siliceous lava is suggested by these analyses of the early lavas.

The lavas vary from dark gray to black, sometimes streaked with raisin brown where the effects of steam have oxidized the iron.

TABLE 1.—*Analyses of early Parícutin lavas*
[Analyses 1-3 by Erma Chadbourn; 4 by W. F. Foshag]

	Quitzocho	Sapichu	Ahuán	Taquí
SiO_2	54. 88	55. 51	55. 59	56. 62
Al_2O_3	18. 38	18. 19	17. 72	17. 54
Fe_2O_3	1. 31	1. 63	1. 33	1. 86
FeO	5. 97	5. 38	5. 99	5. 47
MgO	5. 57	5. 31	5. 60	5. 31
CaO	7. 40	7. 19	6. 99	7. 13
Na_2O	3. 88	3. 92	4. 00	3. 89
K_2O	. 86	1. 10	1. 13	1. 21
H_2O+	. 13	. 08	. 03	. 12
H_2O-	. 05	. 01	. 04	
TiO_2	. 95	. 97	1. 05	1. 00
P_2O_5	. 29	. 31	. 36	----------
MnO	. 13	. 12	. 13	. 12
Total	99. 80	99. 72	99. 96	100. 17

All the lavas of Parícutin volcano are fine grained, almost aphanitic rocks, with sparse scattered phenocrysts of olivine and, rarely, hypersthene. Under the microscope they show the usual basaltic texture. The feldspar of the groundmass is in the usual lathlike, or tabular, form; the pyroxene forms an intersertal aggregate of stumpy prisms. Scattered euhedral to subhedral olivine phenocrysts are always present, and there is a scattering of small magnetite or picotite octahedra. Sometimes small intersertal areas of dark-brown glass remain. The plagioclase feldspar shows little compositional zoning, but the composition varies with crystal size. Large crystals have an average composition of Ab_{49} changing to Ab_{53} in small crystals and Ab_{70} in very small crystals.

EARLY BOMBS

Two ejected bombs recovered by Anguiano and Martínez during the initial outbreak at 10 p. m., February 20, 1943, were preserved by the parish priest, Sr. José Caballero, who generously presented them to us for study. The analyses in the following table show that these early ejected fragments are not bombs of Parícutin lava but probably represent the old lavas underlying the Quitzocho-Cuiyúsuru valley. The topography suggests that these flows were derived from the ancient Cerro de Camiro cone.

FUMAROLES

Fumaroles were abundant in the early lava flows, particularly in the Quitzocho flow, and will be referred to in this report. They were

TABLE 2.—*Analyses of two early Parícutin bombs*

[Bombs 1 and 2, ejected from Parícutin volcano, February 20, 1943. Erma Chadbourn, analyst]

	1	2
SiO_2	51.00	53.14
Al_2O_3	17.54	18.26
Fe_2O_3	2.21	2.03
FeO	5.90	5.27
MgO	8.35	7.25
CaO	8.89	7.93
Na_2O	3.15	3.68
K_2O	.72	.73
H_2O+	.46	.08
H_2O-	.14	.03
TiO_2	1.05	.92
P_2O_5	.23	.22
MnO	.14	.13
Total	99.78	99.67

numerous about the periphery of the flow but rare within the flow itself. In the latter case they appeared to be connected with serious disturbances in the flow, as in large pressure hummocks or where the flow had moved over abrupt terrain (pl. 45*A*). The fumaroles in the Quitzocho flow persisted for more than a year, until covered by later flows, and showed no apparent diminution or change in character. Measurements on the fumaroles of the Quitzocho flow showed temperatures ranging from 105° to 430° C. It was found that the emanations of fumaroles ranging from temperatures of 100° C to 250° C were acid in reaction and yielded a noxious odor of hydrochloric acid, while the higher temperature fumaroles, from 250° C to 430° C yielded an alkaline emanation and a burnt or distinctly ammoniacal odor. The lower temperature, acid fumaroles were associated with altered, brick-red lava and were surrounded by aureoles of colored salts. The higher temperature alkaline fumaroles showed only minor rock alterations.

Field tests of the fumarolic emanations revealed, in addition to abundant steam, the presence of hydrochloric acid, ammonium chloride, and minor amounts of sulfur trioxide, sulfur dioxide, hydrogen sulfide, and carbon dioxide. Lead and free chlorine were very rare. Condensable solids, collected in tubes introduced in the fumaroles, showed a surprising simplicity of composition consisting of ammonium chloride with small amounts of sodium and potassium chlorides and minute quantities of fluorides (Foshag and Henderson, 1946).

The reaction of these emanations with the wall rock of the fumaroles, or with overlying ash, yielded secondary chlorides of iron and ammonium, calcium, magnesium, and others; an oxychloride of aluminum, a hydrous basic chloride of magnesium, and similar salts. Sulfur was a very rare and inconspicuous deposit.

In addition to the fumaroles, there were vents that yielded only steam, presumably where hot lava was in contact with moist ground or a similar source of water. Buried stream channels, as of Arroyo de Nureto, localized a line of steam emanations during the rainy season. Trees engulfed in the lava yielded distillation products and resembled fumaroles in appearance. The three types of emanations could, however, be readily distinguished. The vapors of steam were pure white; the emanations from the fumaroles were bluish, owing to their content of finely divided particles of condensed solids; and the distillation from organic matter, such as trees, had a brownish tint.

High-temperature fumaroles, 1,100° C to 1,200° C were abundantly associated with the hornitos above the Taquí flow. The gaseous emanations, with a strong odor of hydrochloric acid, were frequently too noxious to permit entry into the hornito area. At times, bright-yellow and orange fumarolic deposits colored large areas of the lava crust. These fumaroles were usually accompanied by burning gases, and their orifices were lined with a fused rock coating. Hematite, magnetite, apthitalite, and thenardite formed in the vents. Later, aluminum and other chlorides formed by the interaction of the gases and the lavas.

Frequently the rains showed a mild acid reaction and contained soluble salts derived from the eruptive column of the volcano.

VOLCANIC SOUNDS

Reference will be made frequently in this report to the various sounds heard during the eruptions of Parícutin volcano. In the course of our observations we were concerned with the origin and interpretation of these sounds, particularly those emanating from inaccessible places, as the crater in full operation. In some cases we were definitely able to determine the cause of the sound, and in others to gain a reasonably good indication of their origin.

Wilcox (1947) has listed various sounds common at Parícutin. He distinguishes 11 distinct types, without, however, indicating their origins. Some of these 11 categories may have a similar origin but vary in intensity or duration.

One of the common sounds is usually compared by everyone who hears it to the beating of a heavy surf upon a shore. It is associated with the bursts of bombs from the crater, the successive blasts yielding a pulsating or surflike roll. This sound is undoubtedly due to the combined swish of falling bombs. A softer surging, like the sough of the wind in the pine trees, probably results from the fall of lapilli or the smaller bombs. Following this surflike noise, one can frequently distinguish the slap of the bombs falling on the slopes of the cone.

Sounds from the interior of the crater are muffled by the crater walls. These sounds originate, chiefly, in the eruptive vents of the crater but are modified by the shape and size of the vent and the intensity and character or period of the emission. Several visits to the rim of the crater during moderate eruption have given us some insight in the interpretation of these sounds. A deep throaty roar results from the rush of vapors from a small vent; a low growl from the intermittent emission of a similar vent. A vapor column from a crater vent produces a thunderlike roll, which may be a grating roar when the velocity is high.

Other sounds are definitely connected with lava vents. Rhythmic sounds like a locomotive are noticeable during periods of lava emission and presumably connected with the rising lava column. We have noticed these sounds only about small, newly opened eruptive orifices and not with long established lava vents.

A sibilant sound, which close by becomes a strong and continuous hiss, is produced by the forced emission of vapors from the small vents of the hornitos that form upon the lava crust. This sound is sometimes perceptible from several miles away. A sharp whistle is sometimes produced by the small but rapid whirlwinds that are made by the escape of gases from incandescent and flowing lava.

Sharp pistollike reports accompany the short, lightning discharge in the rising eruptive column. Frequently these lightning discharges are hidden in the eruptive column, or are not visible in the light of day. The lightning discharge may appear as a point discharge, with a resulting sharp crack or report. Even the largest bolts are short discharges.

The sounds were frequently suggestive when certain phases of activity were hidden from view.

PRE-PARÍCUTIN HISTORY

MEXICAN VOLCANIC AXIS

The Mexican Volcanic Axis forms a belt about 900 kilometers long and 70 to 100 kilometers wide, extending from San Martín Tuxtla on the Gulf of Mexico to Colima and Tepic on the Pacific coast. It lies between lat 18° and 19° N., except in the extreme west, where it broadens out to extend as far north as the 22d degree of latitude. It is transverse to the other volcanic axes of North America, the coast range volcanoes of California and the Volcanic Axis of Central America, both of which parallel closely the Pacific coast of the continent. This zone includes the active volcanoes (from east to west) San Martín Tuxtla (active in 1793), Orizaba (1687), Popocatepetl (1920–24), Jorullo (1759–?), Colima (1913), Ceboruco (1870–75), and San Juan (1859–?), as well as the prominent but inactive or extinct volcanoes, Nevada de Toluca (4,565 meters), Malintzin (4,115 meters), Ajusco (3,950 meters), Tancítaro (3,845 meters), and innumerable smaller cones and other volcanic edifices (fig. 108).

This volcanic zone occupies a critical position in the epeirogenic structure of North America, separating, as it does, the high central plateau (Mesa Central) of Mexico from the rugged and deeply dissected terrain of Meso-America and hiding beneath its cover of late volcanic products the transition between these two diverse geologic provinces. This critical position of the Volcanic Axis has already been emphasized by Pedro Sánchez (1935). In his opinion this axis fixes the southern limits of North America. That portion of Mexico lying to the south has the characteristics of Central America and is, therefore, to be included in Meso-America.

The area lying north of the Volcanic Axis, the Mesa Central, is a high plateau with a general altitude between 2,000 and 2,500 meters. Its rocks consist principally of limestone of Mesozoic age, covered in many places by volcanic flows and deposits of middle or late Tertiary age. The principal structural trends in this province are northwest. The area lying to the south of the Volcanic Axis, the Sierra Madre del Sur, in comparison, is extremely rugged, complex in geologic structure, and deeply eroded. Crystalline rocks and many intrusions characterize the province, while limestone of Mesozoic age and Tertiary volcanic rocks are restricted largely to remnants upon the higher eminences.

In addition to these topographic and geologic differences, the two provinces show striking seismic contrasts; the Mesa Central is an area of stability, the Sierra Madre del Sur one of strong and frequent earthquakes.

There are marked gravitational differences, too, between the two provinces. North of the Volcanic Axis the gravitational anomalies are small, increasing in negative value as one approaches the axis itself, where the highest anomalies are recorded. Continuing south the negative anomaly drops rapidly in value until it reaches zero (Sanchez, 1935; Carreño, 1943).

The Volcanic Axis is a Pliocene to Recent superposition of volcanic edifices upon the transition zone of the Mesa Central and the Sierra Madre del Sur. The earlier lavas are largely andesitic in character, but there are sporadic occurrences of rhyolitic effusions. Later lavas are andesite-basaltic to balsaltic in composition. The earlier cones are huge edifices (Orizaba, Ixtaccihuatl, Tancítaro), while the late

338669 O—55——2

ones make up for their comparatively small size by their abundance. In most portions of the Volcanic Axis, the volcanic products completely mask the underlying formations.

It is worthy of note that along the eastern plateau front of Mexico, a scattering of recent volcanic cones are similarly distributed. Along the foot of the eastern plateau scarp, within the small folded valleys of the plateau front, and along the eastern plateau summit, small recent basalt cones and flows can be seen; while within the high central plateau, recent basaltic cones are rare. Most striking of these interior basaltic emissions are the extensive rugged flows of the Breñal, in Durango.

GEOLOGIC SETTING

The Michoacán volcanic province occupies that portion of the Mexican Volcanic Axis lying between the Sierra de Ozumatlán and Lago de Chapala. Here the transition zone between the Mesa Central and the Sierra Madre del Sur is relatively narrow and sharp but completely mantled by the volcanic cover of the Volcanic Axis. The plateau, which at Uruapan has an altitude of 1,600 meters, drops abruptly to the Río de Tepalcatepec (200 meters), at the foot of the plateau front. Late volcanic edifices and deposits completely cover the plateau front; volcanic agglomerate deposits and a few scattered ash cones occupy the lower valley slopes as far as the Río de Tepalcatepec. Beyond the Río de Tepalcatepec, no more late volcanic cones or deposits are to be found, and middle Tertiary effusive rocks are seen as scattered remnants of rhyolite flows and tuffs that crown some of the higher eminences, particularly in the low country lying south of La Huacana, along the lower Río de Tepalcatepec and Río de Las Balsas. Since middle Tertiary time, the region south of the Río de Tepalcatepec has seen no volcanic activity; while immediately to the north, vulcanism has been intense in late Pliocene (Cerros de Tancítaro) and particularly in Pleistocene and Recent times. The relationship of the Volcanic Axis to the Sierra Madre del Sur province is nowhere more clearly defined than in the zone immediately south of the Parícutin area.

From our knowledge of the geology of the area (pl. 14) between the Río de Tepalcatepec and Río de Las Balsas and the Pacific Ocean, the Tierra Caliente, we may divide the area into two distinct parts. Between the Río de Tepalcatepec and the Pacific Ocean, the rocks are largely of sedimentary nature, principally black fissile nonfossiliferous slates which from their similarity to slates in the State of México and other areas, are presumed to be of Jurassic age. More advanced metamorphism has converted these slates into phyllites in many places. Red sandstone and conglomerate, exposed along the Pacific coast and as minor patches inland apparently lie below these slates and may be of Triassic age Above the slates and crowning a few of the highest ridges is limestone similar to the Cretaceous limestone in other Mexican occurrences.

Large masses of diorite and smaller ones of diorite, monzonite, granite, and adamellite are intrusive in these sedimentary formations. Residual masses of rhyolite, rhyolite tuff, or andesite cap a few of the higher eminences in the northern part of the area.

The region lying between the plateau front and the Río de Las Balsas has a rather different lithological character. The oldest formation exposed is a melaphyric basalt composed of aphanitic, amygdaloidal, and porphyritic types. The amygdaloidal form frequently carries secondary epidote, calcite, and quartz in cavities. The porphyritic type is widespread and striking in appearance, with phenocrysts of labradorite reaching a centimeter in size in an aphanitic groundmass.

Numerous large and small dikes and large masses of diorite are intrusive into these basalts; in some places, as at Inguarán and Oropeo, they are associated with copper ore deposits.

Rhyolite flows and tuffs cap the higher peaks and mesas of both melaphyric basalt and the intrusive dioritic rocks. These rhyolites are similar to those of the Mesa Central, where they are much more widespread and rest upon sedimentary formations of Mesozoic age or upon andesites of middle Tertiary age.

Although the rocks underlying the Volcanic Axis in the Michoacán area are completely covered by late lavas, some knowledge of the underlying geology can be gained by a study of the xenolithic bombs found in the old ash cones and the inclusions in the lavas. Every volcanic edifice of the region yields some of these inclusions; in some they are abundant. Parícutin volcano has yielded xenoliths of quartz monzonite, granite, and rhyolite. The limited collection of these xenoliths now at hand, made over a wide area of the Michoacán province, indicates that the sublava basement has its closest affinities with the area lying between the Volcanic Axis and the Río de Las Balsas and that it is principally composed of intrusive granitic and dioritic rocks with some rhyolite. As yet no melaphyric basalt has been recognized among the xenolithic materials, nor limestone, slate, phyllite, nor crystalline metamorphic rocks. This suggests that the rocks of the Balsas–Tepalcatepec area, rather than the rocks of the Pacific littoral, or those of the Mesa Central, underlie the Parícutin area.

One of the important elements of the Mexican Volcanic Axis is the Michoacán volcanic province, extending from the Sierra of Ozumatlán in central Michoacán to the western shores of Lago de Chapala, in

Jalisco. To the north, this province passes gradually into the lower Bajío of Guanajuato and to the south terminates abruptly at the foot of the plateau front and the beginning of the Tierra Caliente.

The Sierra de Ozumatlán, the eastern border of the Michoacán basaltic province, is a rugged mountain mass of dissected older andesitic lavas, which show few, if any, late Tertiary or Recent volcanic emissions. To the east of the Sierra de Ozumatlán, in the valley of the Río Taximaroa, of eastern Michoacán, volcanic cones and flows again become conspicuous but in much fewer numbers and more scattered than in western Michoacán.

To the north, the Michoacán province passes gradually into a province of earlier rhyolitic rocks of Guanajuato and southeastern Jalisco. Late volcanic edifices become progressively fewer until the Río Lerma is reached, beyond which few basaltic cones or flows are noted, the topography being characterized by elongated ridges or mesas of rhyolitic flows and tuffs. The last striking manifestation of late basaltic vulcanism in this direction is the nest of well-preserved cones in the valley of Río de Santiago.

The western limits of the province, like the northern, are not easy to define, because the province again passes gradually into a coastal province of rocks of Mesozoic and middle Tertiary age, where the later Tertiary volcanic manifestations are dominated by the emissions of the large Colima and Ceboruco volcanoes. The southern limit, on the other hand, is strikingly abrupt, terminating at the foot of the plateau front. On the plateau slope the rocks are exclusively late Tertiary to Recent basalts or related lavas. From the foot of the plateau front through the Tierra Caliente, late volcanic formations are absent. This abrupt change is best shown along the plateau slope between Uruapan and the Río de Tepalcatepec, where many well-defined cones are evident; while beyond the Río de Tepalcatepec, no late Tertiary or Recent volcanic edifices are found.

Studies by Williams (1950) in the Uruapan region indicate that there are three general phases of Tertiary vulcanisms in the Michoacán volcanic province (excluding an early volcanic sequence of melaphyric lavas that probably underlies part of the province). An early phase represented by the Zumpinito lavas is probably equivalent to the lavas of the Sierra de Ozumatlán that limit the basaltic province on the east and perhaps, also, to the lavas that cap the higher eminences south of the Río de Tepalcatepec. A second phase includes the emission of lavas that formed the high mass of Cerros de Tancítaro and other coeval cones. A more conspicuous phase, however, is that of the numerous later and recent cones and flows, of which Jorullo and Parícutin are the newest manifestations.

The eruptive rocks of this last phase range from andesite through andesite-basalt and basalt to olivine-basalt. The older cones, higher in elevation and more eroded than the later cones, are chiefly andesitic. The late Pleistocene and Recent cones retain their original features but little altered and are principally basaltic.

No alignment or regular pattern of distribution of these cones is apparent to indicate a control by prominent fissures. Nor is there any readily apparent evidence that the late cones, once they had ceased activity, were the loci of later renewed outbursts. Any new activity established itself in a new locus, such as Jorullo or Parícutin, independent of any apparent previous structure.

LOCAL GEOGRAPHY

Before the advent of Parícutin volcano, the principal town of the region was San Juan Parangaricutiro. As is the custom in naming towns in southern Mexico, the designations frequently combine the Spanish name of the town (San Juan) with its indigenous name (Parangaricutiro). San Juan Parangaricutiro was also the cabecera, or governmental center, of the municipio, a political subdivision corresponding somewhat to an American township. Its inhabitants were largely of mixed Spanish-indigenous blood. Included within the municipio of Parangaricutiro are the villages of Angahuan, Parícutin, Zirosto, and Zacán. San Juan Parangaricutiro was also the commercial center of the region. It had a population of about 4,000 people. The beautiful 18th century church of the town housed the famous Señor de los Milagros, the figure of a saint venerated throughout the region. An annual celebration and fair was held in honor of this saint on each 14th day of September.

Two kilometers south of San Juan Parangaricutiro was the village of Parícutin, consisting of about 150 Tarascan families. Parícutin was famous for its fruit, particularly pears. West of San Juan Parangaricutiro is Zirosto, also a Tarascan village. About 2 kilometers northeast of San Juan Parangaricutiro is the village of Angahuan, a pure Tarascan town, and now, since the destruction of San Juan Parangaricutiro, the largest town of the municipio. A beautiful ancient Franciscan chapel faces the main plaza of the town. Zacán is a Tarascan village to the north of San Juan Parangaricutiro and at a higher elevation.

About these villages lie the cultivated fields of the villages, devoted chiefly to the growing of corn, except on the higher elevations where wheat prospered. Surrounding the fields are wooded old volcanic cones or ridges formed by old lava flows. Rich cornfields occupy the craters of many of these old volcanoes, and oak and pine forests, which are a source of timber and turpentine, cover the volcanic slopes.

Three kilometers south of San Juan Parangaricutiro and 2 kilometers southeast of Parícutin lay a small valley, bordered on almost all sides by pine-clad volcanic hills. On the north was Cerro de Jarátiro, with three ancient but well-preserved craters; to the southeast is the conical wooded mass of the extinct volcano Cerro Prieto, with several alluvium-filed craters; to the south Cerro de Camiro, Cerro del Cebo, and the lower slopes of Cerros de Tancítaro, with its incumbent later cones; and to the west the steep front of the volcanic Mesa de Cocjarao and the eroded cone of Cerro de Canicjuata.

Among the parcels of land within this valley were two adjoining ones: Llano de Quitzocho and Llano de Cuiyúsuru [3] (fig. 109), both belonging to Parícutin. They were separated by a stone wall and were considered valuable for their forest lands and cultivated fields. Barbarino Gutiérrez owned Quitzocho, and Dionisio Pulido owned Cuiyúsuru. A large rock, called Piedra del Sol because it caught the early morning rays of the sun, was a nearby boundary marker. Lava flows now completely fill this small valley, and it is difficult for one who did not know it before the lavas came to picture its original charm. It had a diameter from north to south of 2¼ kilometers and from east to west, 1½ kilometers. The south end of the valley was occupied by several old lava flows, whose steep fronts formed wooded scarps and crests bore cultivated fields. From these volcanic terraces the ground sloped gently north toward Cerro de Jarátiro. The lowest point in the valley at the foot of Cerro de Jarátiro had an altitude (by aneroid)

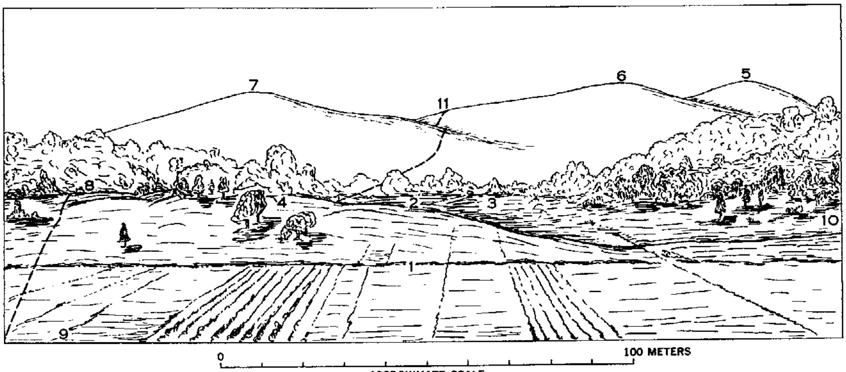


FIGURE 109.—Quitzocho-Cuiyúsuru valley and surrounding area before the outbreak of Parícutin volcano as reconstructed from observations of early volcanism. 1, Quitzocho; 2, Cuiyúsuru; 3, Pastoriu; 4, Uricua Llostiro; 5, Tancítaro; 6, Cebo; 7, Camiro; 8, Piedra del Sol; 9, Sherecuaro; 10, Parícutin Arroyo; 11, Parangaricutiro-Parícutin boundary—passes in front of foreground and follows ridge along Cebo and Tancítaro. Road from Camiro hill, San Nicolas, and Teruto follows left boundary of sketch, Uruapan-Parícutin road follows front boundary.

[3] The authors of this chapter prefer the spelling Cuiyútzuru, as used in the official archives of the municipio of San Juan Parangaricutiro, but for the sake of consistency have agreed to follow the spelling used in previous chapters of this bulletin.

of 2,375 meters. To the northeast, the valley merged with the cultivated fields through Jarumagagitiro, Sherecuaro, La Lagunita toward Tipacuaro and other parcels of land lying at the eastern foot of Cerro de Equijuata and Cerro de Capatzun.

The valley was drained by Parícutin Arroyo, whose principal headwaters were between the old volcanic cone of Cerro de Canicjuata and the high lava terrace of the Mesa de Cocjarao. Near its headwaters was the spring that supplied Parícutin village with its potable water. Parícutin Arroyo carried a flow of water only during the rainy season. A small tributary, usually dry, passed through the cultivated lands of Cuiyúsuru. Parícutin Arroyo left the valley through a narrow gap between the lower slopes of Cerro de Canicjuata and Cerro de Jarátiro near the parcel Titizu, where it was a steep-walled gully about 4 meters deep. It then passed the eastern edge of Parícutin village, turned west, and joined the Arroyo Principal of San Juan Parangaricutiro in the fields of Huirambosta.

At the eastern foot of Cerro de Jarátiro was the parcel of land La Lagunita, a small depressed area sometimes occupied by an ephemeral pond. Drainage to the northeast was not well defined; a few shallow arroyos joined the Arroyo Principal above San Juan Parangaricutiro, along the San Juan Parangaricutiro–Uruapan road.

Except for trees along Parícutin Arroyo and its tributaries and a few small copses of pines, the valley land was cultivated. No permanent dwellings were in the valley, but stone walls or fences separated one parcel of land from another. The little used Uruapan–Parícutin road followed the foot of Cerro de Jarátiro, and wood roads and horse trails passed through the forest lands. The road to Camiro, Teruto, San Nicolás, and other points skirted the valley on the east.

One of the minor features of the valley that attracted some attention was a small hole in the farm, Cuiyúsuru. Dionisio Pulido, owner of the farm, described it as having a diameter of 5 meters and a depth of 1½ meters. Sra. Severiana Murillo, now an old lady, recalled how, as a child more than 50 years ago, she played about this pit. She remembers it well because her father warned her to avoid the spot, because, he said, it was the entrance to an old Spanish mine (although no mining activity has been recorded in the region) and because one frequently heard subterranean noises near the hole, as if made by falling rocks. The children amused themselves about this hole because it emitted a pleasant warmth, and they probed it with sticks without touching a bottom.

Robles Ramos (1943) quotes Vicente Mediano as relating that he noted a depression that had formed in the field as early as the month of August 1942, and that a kind of mist was emitted from it during a period of rains, but he attached little importance to it. Dionisio

Pulido sometimes referred to this pit as a resumidero, a hole in a closed basin through which storm waters escaped during the rainy season.

As is usual in these regions of Michoacán, the tillable lands are privately owned, but the forest lands belong, in large part, to the villages. The forests, being sources of lumber and turpentine, are an important asset to the community. The owners of the parcelas, or farms, live in the villages, and the workers travel each day with their oxen and tools from the village to their fields or to the forest, returning in the evening to their homes.

LOCAL HISTORY

The tragedy of the people of the region about Parícutin began, according to their beliefs, many years ago. Then San Juan Parangaricutiro, the town which became the important center of the area, the greatest in influence, and the governing head of the municipio, bought lands from other villages to add to its municipal domain. Parícutin, too, sold lands to San Juan Parangaricutiro; but San Juan Parangaricutiro, according to those of Parícutin, took to itself more than it had purchased. Parícutin offered to settle for "4 cargas más 2 cuartillos de pesos," in accordance with an ancient manner of payment; but no accord or compromise could be agreed upon. This situation led to constant and acrimonious disputes, until there developed such a deep feeling of enmity that those of one village hardly dared pass upon the lands of the other. This animosity led to frequent altercations on the disputed lands, during one of which Nicolás Toral, of Parícutin, lost his life, almost on the spot where the new volcano was to break forth.

The ecclesiastical authorities of the parish, desiring that the dispute should cease and the two villages live in harmony, placed upon Peña del Horno, a huge rock high on the flanks of Cerros de Tancítaro, a large wooden cross with an inscribed plaque of silver, facing the part of the valley that included the disputed lands. To inaugurate this anticipated happy period, the parish priest, in the presence of a large assemblage of people, held a solemn mass and blessed the sacred symbol.

Some days passed in peace, until it was discovered that the cross had been cut down and had disappeared, an act of sacrilege committed perhaps under the misapprehension that the cross was intended to fix the disputed boundary line. The finger of suspicion pointed to a poor stutterer, Padilla of Parícutin, who henceforth lived in some anxiety and danger.

The Tarascan tharepeti, a council of patriarchs that met periodically to deliberate matters of communal interest and to augur the signs of the future, considered this event with dark forebodings and prognosticated a punishment without equal, a punishment that would cause their misery and ruin. Sra. Justina Sánchez, of Parícutin, no doubt influenced by the prediction of the tharepeti, saw in her dreams a fire issue from the earth and consume everything. This incident, which the outbreak of the volcano seemed later so strikingly to confirm, profoundly impressed many of the people.

While the sacrilege of the cross was generally considered the major sin that brought the destruction to the region, there were persons who believed that their personal slight sins were a contributory factor.

In spite of these beliefs as to its ultimate cause, the people recognized the volcano as a natural phenomenon and readily connected the growing cone and the flowing lava with similar features of the region with which they had an everyday familiarity—the wooded cones, the cultivated valleys and benches, and the rugged malpais.

BIRTH OF PARÍCUTIN VOLCANO

EARTHQUAKES

Early February is the season when the villagers are in their fields, cleaning the land or otherwise occupied in preparing for the first plowing of the year. It was then that the first premonitive tremors were felt and the first subterranean noises heard.

Celedonio Gutiérrez has given us some account of the few weeks preceding the outbreak of the volcano, a translation of which is given here:

> The year 1943 began. When I visited a friend on a ranch called Titzicato, some few kilometers south of where the new volcano broke forth, he told me that some tremors had already begun in these places and they heard many noises in the center of the earth. These tremors began to be felt in San Juan [Parangaricutiro] the following month, the 5th of February, at midday, and every day until the 20th. During these 15 days of tremors there were some stronger than others; when we heard the subterranean noises we awaited the tremor. According to the noise the movement of the earth was strong or weak. They followed each other almost every minute. If they were delayed the noise or the tremor was stronger.
>
> The people could not feel secure nor have confidence to remain in their houses to sleep. They knelt down frequently to pray to God that the earth would not sink, such was the movement during so many days of earthquakes. They brought forth the Image of the Santo Cristo Milagroso, of this village, in procession and the earthquake ceased. I write this because I have seen it and not because it was to told me.

The priest Sr. José Caballero, then parish priest of San Juan Parangaricutiro, related that light earth tremors began to be felt on February 7, 1943. On the 15th, at 5 p. m., they reached an alarming intensity. At 10 a. m. on the 20th subterranean noises were heard in San Juan Parangaricutiro; and the tremors were then, without exception, oscillatory. Sr. Caballero recalled that when he first came to San Juan Parangaricutiro and Parícutin as parish priest in 1933 the walls of the churches of both villages were fissured to a notable extent, suggesting to him that tremors were already active at that early date.

Professor Ruperto Torres L., editor of a newspaper at Uruapan and a resident of that town for many years, related that some 2 years before the outbreak of Parícutin volcano, rather weak tremors were felt in the region. No particular significance was ascribed to them, since they were generally considered to be tectonic tremors with an origin in the Pacific Ocean, a not infrequent occurrence in the littoral of Colima, Michoacán, and Guerrero. According to Professor Torres, tremors were again felt on the 5th of February 1943, but no importance was attached to them. By February 10 the tremors were more frequent and of greater intensity but were still considered to have a distant origin. On the 20th a messenger from San Juan Parangaricutiro arrived in Uruapan with word from the presidente, Sr. Felipe Cuara Amezcua, to the presidente of Uruapan, reporting in alarming terms that the region of San Juan Parangaricutiro and Parícutin was experiencing such strong and frequent tremors that neither the municipal nor church authorities, nor the people, knew what to do. On the same evening a second messenger arrived with word that the tremors had ceased but that a volcano had broken out between the fields of Cuiyúsuru and Quitzocho. An urgent plea for help was then dispatched to the Governor of the State at Morelia.

According to Sr. Felipe Cuara Amezcua, earth tremors began to be noticeable on February 5, 1943, increasing in number and intensity until more than 200 were experienced in a day. The tremors became so frequent and strong that it was feared that the church at San Juan Parangaricutiro, with its massive masonry walls, would collapse. The parish priest, José Caballero, had the image of the saint El Señor de los Milagros removed to the plaza, facing, by a strange coincidence, the point where the new volcano would break out. These tremors were accompanied by subterranean noises. Both the tremors and noises seemed to center in Cuiyúsuru, which led him to believe that Cerro Prieto, an ancient cone which lay immediately adjacent to the farm, would break its agelong rest and erupt.

According to Robles Ramos (1943) the earthquakes varied between intensities 3 and 4, Mercalli's scale.

SOURCES OF INFORMATION

For about a week or more before the initial outbreak of Parícutin volcano, accounts appeared in Mexico City newspapers mentioning the recurrent earth tremors in the Uruapan region. In one of these accounts the presidente municipal of San Juan Parangaricutiro, Sr.

Felipe Cuara Amezcua, predicted a new volcanic outbreak. In spite of this warning, available geologists were unprepared for the event that followed. Fortunately, the manifestation was witnessed by several inhabitants of the area, Tarascan Indians, whose keen perception and innate knowledge of natural phenomena are responsible for the first adequate account of the birth of a new volcano.

Among the actual eyewitnesses to this unusual event, we were able to interview Sr. Dionisio Pulido, owner of Cuiyúsuru, the farm that brought forth the volcano; Sra. Paula Cervantes Rangel de Pulido, his wife; Sr. Dolores Pulido, his brother; all of Parícutin; and Sra. Aurora Cuara of San Juan Parangaricutiro.

Demetrio Toral, a laborer from Parícutin employed by Pulido as helper, was plowing land at Cuiyúsuru. He had just completed a furrow and was about to turn his plow when the first outbreak of the volcano occurred almost in the exact furrow he had just drawn. This remarkable circumstance has led some people into the belief that Toral "plowed up the volcano." Toral, a deaf mute, died soon after in Caltzontzin.

It has been reported that José María Isidro was also present at the outbreak of the volcano, but we have been unable to locate him.

A lad of San Juan of Parangaricutiro, hearing the accounts of the outbreak being discussed by the townspeople in the plaza, went to Ticuiro, a field near the edge of town, and took photographs (pl. 16*A*, *B*) of the event. The time was about 5 p. m.

Immediately after the outbreak of the volcano, the presidente municipal of San Juan Parangaricutiro sent a group to the spot to investigate the event. Of the group members we succeeded in finding Juan Anguiano Espinosa, Jesús Martínez, and Luis Ortíz Solorio and obtaining from them an account of the events that occurred an hour or so after the initial outbreak.

Among the officials of the municipio who contributed accounts were the presidente municipal Sr. Felipe Cuara Amezcua and the parish priest, Sr. José Caballero. Sr. Celedonio Gutiérrez, of San Juan Parangaricutiro, has maintained a diary since the beginning of the volcano's activity and has given us access to a copy of this valuable document. Finally, the event is succinctly described in the official records of the municipio of San Juan Parangaricutiro, a certified copy of which Sr. Cuara Amezcua prepared for us.

DIONISIO PULIDO

Dionisio Pulido was a resident of the village of Parícutin. For 31 years he was owner of Cuiyúsuru farm. He is now a resident of Caltzontzin, near Uruapan, a village organized to accommodate the former inhabitants of Parícutin. His farm was divided into three parts: one which he worked himself, one which he shared with his brother Dolores, and one which he rented on shares to others. Upon his land was a small hole (mentioned by Sra. Murillo) with an apparent depth of 1½ meters. Year after year he and Dolores cast dirt and debris in this hole without succeeding in filling it. Frequently Pulido hid his ox yoke and plow in it to spare the trouble of bringing them to Parícutin. Before January 1943 nothing unusual about his farm attracted his attention. Its picturesque and peaceful environment pleased his Tarascan nature. Never, not even on the day of the initial volcanic outbreak on Cuiyúsuru, did he note any unusual warmth in the ground, as has been so frequently stated in popular accounts of the event.

On February 20, 1943, Pulido left his village, going to his farm to prepare the fields for the spring sowing. He was accompanied by his wife, Paula, his small son, who would watch the sheep, and Demetrio Toral, his helper, to begin the plowing. The day was calm, and the sky was clear. Pulido's account, as he related it to us, follows:

In the afternoon I joined my wife and son, who were watching the sheep, and inquired if anything new had occurred, since for 2 weeks we had felt strong tremors in the region. Paula replied, yes, that she had heard noise and thunder underground. Scarcely had she finished speaking when I, myself, heard a noise, like thunder during a rainstorm, but I could not explain it, for the sky above was clear and the day was so peaceful, as it is in February.

At 4 p. m. I left my wife to set fire to a pile of branches which Demetrio and I and another, whose name I cannot remember, had gathered. I went to burn the branches when I noticed that a cueva,[4] which was situated on one of the knolls of my farm, had opened,[5] and I noticed that this fissure, as I followed it with my eye, was long and passed from where I stood, through the hole, and continued in the direction of Cerro de Canicjuata, where Canicjuata joins Mesa de Cocjarao. Here is something new and strange, thought I, and I searched the ground for marks to see whether or not it had opened in the night, but could find none; and I saw that it was a kind of fissure that had only a depth of half a meter. I set about to ignite the branches again when I felt a thunder, the trees trembled, and I turned to speak to Paula; and it was then I saw how, in the hole, the ground swelled and raised itself 2 or 2½ meters high, and a kind of smoke or fine dust—gray, like ashes—began to rise up in a portion of the crack that I had not previously seen near the resumidero. Immediately more smoke began to rise, with a hiss or whistle, loud and continuous; and there was a smell of sulfur. I then became greatly frightened and tried to help unyoke one of the ox teams. I hardly knew what to do, so stunned was I before this, not knowing what to think or what to do and not able to find my wife or my son or my animals. Finally my wits returned and I recalled the sacred Señor de los Milagros, which was in the church in San Juan (Parangaricutiro) and in a loud voice I cried, "Santo Señor de los Milagros, you brought me into this world—now save me from the dangers in which I am about to die;" and I looked toward the fissure whence rose the smoke; and my

[4] Variously referred to by Pulido as a cueva (cave or grotto), resumidero (a hole or crevice, into which water disappears during the rainy season), or agujero (a hole).

[5] In another account Pulido described the initial noise as a pop, as one hears upon opening a bottle of carbonated beverage.

fear for the first time disappeared. I ran to see if I could save my family and my companions and my oxen, but I did not see them and thought that they had taken the oxen to the spring for water. I saw that there was no longer any water in the spring, for it was near the fissure, and I thought the water was lost because of the fissure. Then, very frightened, I mounted my mare and galloped to Parícutin, where I found my wife and son and friends awaiting, fearing that I might be dead and that they would never see me again. On the road to Parícutin I thought of my little animals, the yoke oxen, that were going to die in that flame and smoke, but upon arriving at my house I was happy to see that they were there.

Upon his arrival at Parícutin, Pulido reported the event to the Chief of the Parícutin subdivision, Sr. C. Agustín Sánchez, who then accompanied him to San Juan Parangaricutiro to report to the presidente of the municipio, Sr. Felipe Cuara Amezcua.

On the following day Pulido drove his oxen to the forest to graze and then went to his farm to see what had occurred. When he arrived there at 8 a. m., he saw that a hill, which he estimated to be 10 meters high, had formed and that this mound emitted smoke and hurled out rocks with great violence.

Alfonso de la O Carreño (1943) states that a light seism accompanied by subterranean noises and followed by a distant detonation was perceived at San Juan Parangaricutiro on Saturday, the 20th, at 5:20 p. m. Pulido reported to him that, at 4 p. m. and before, he walked about his farm hearing noises like those of a heavy freshet, that the sky was cloudless, and that he looked in all directions to localize the noise. Then suddenly he saw a large column of black smoke arise from a depression, and a fissure, 5 centimeters wide, open in the soil; and he was able to follow the eastward-trending fissure with his eye for 30 meters.

PAULA PULIDO

Paula Cervantes Rangel de Pulido, wife of Dionisio Pulido, accompanied her husband to watch the sheep. She is Tarascan; and although she understands Spanish, she does not speak it. Dolores Pulido acted as our interpreter. Sra. Pulido also related her account to Sra. Amalia Vargas de Ortiz, of San Juan Parangaricutiro, who in turn told it to us. According to Sra. Ortiz, Paula Pulido spent part of the day in the shade of an oak, watching the sheep grazing on the sparse herbage. As the sheep moved on she changed her position to another nearby tree, and it was from there that she saw a small whirling dust column (remolinito) follow a small fissure in the soil, moving from a point called Quijata to Cuiyúsuru, a distance of about a kilometer. A kind of fissure 5 centimeters wide and 30 centimeters deep opened as the dust column moved toward Cuiyúsuru depositing a pale-gray dust. The column stopped near the oak tree she had left a short time before, and a hole 30 centimeters wide opened, and a smoke began to rise. Her first reaction was one of surprise and delight in watching the "pretty remolinito" as it traveled along, fissuring the soil.

Her account to us, through Dolores Pulido, follows:

> About 4 p. m., after talking to my husband, I heard a kind of loud whistle, like the noise of water falling on live coals or hot embers. This noise was completely distinct from the underground noise I had been hearing, and the trees swayed strongly and continuously. I was about 100 meters from the place where these things took place, when I saw, issuing from a crevice that had formed, a little cloud of gray and I smelled an odor like sulfur, and I noticed that some pines about 30 meters from the orifice began to burn. I called to my husband. Then the ground rose in the form of a confused cake above the open fissure and then disappeared, but I cannot say whether it blew out or fell back—I believe it swallowed itself. I was sure the earth was on fire and it would consume itself. From the fissure arose a gray column of smoke, without force, depositing a fine gray dust.

Now very much frightened, Paula Pulido fled to Parícutin and there awaited with great anxiety some word of the fate of her husband.

DOLORES PULIDO

On the afternoon of February 20, Dolores Pulido was working in the forest on Cerro de Janánboro. He saw a column of smoke arising from Cuiyúsuru; and since he was part owner of land there, he went to see what was taking place. He reached the spot about 6 p. m. and saw smoke issuing from a hole in the ground. About this vent were low mounds of fine gray ash. He was unable to approach closer than 8 meters because of falling stones. He then took fright and fled. He returned to the place the next morning and found a gentle rain of "sand" falling about the spot.

AURORA CUARA

All during the day of February 20, while Gregorio Cuara and his family were at their farm at San Nicolás about 20 kilometers from San Juan Parangaricutiro, they felt strong tremors and heard subterranean noises resembling the noise of a motor or a stone rolling down a rocky slope. The trail from San Nicolás to San Juan Parangaricutiro passes Quitzocho and almost at the foot of Piedra del Sol. Sra. Aurora Cuara, a Tarascan woman of unusual intelligence and perception, and one of her children were returning to San Juan Parangaricutiro by this path and had reached Piedra del Sol about 4:30 p. m. There Sra. Cuara saw Pulido gathering branches and weeds into a pile and saw his helper, Toral, complete a furrow in his plowing, passing over the precise point where the earth was to open a moment later. As the helper was about to make the turn to commence a new furrow, a fissure split the earth in a direction toward Cerro de Canicjuata. The earth rose as a wall 10 meters long and 2 meters wide to a height of about a meter, and a gray smoke of a very fine gray dust ascended. Although greatly frightened, Sra. Cuara climbed Piedra del Sol, in order to observe better this unusual event. The fissure was no more than 50 meters away. In addition to the small dust column, she also saw "sparks" thrown out. She watched Pulido try to help unyoke the oxen; and when he fled in fright she, too, lost courage and, with her child, ran toward the town. A drawing from a sketch by Sra. Cuara (fig. 110) shows the position of the various features and eyewitnesses as she saw them.

At 10 o'clock at night she could clearly see from San Juan Parangaricutiro, between the pine trees of the forest, incandescent bombs thrown into the air. Sometime between 11 and 12 p. m., the new volcano began to roar, incandescent stones were hurled up with great force, and a column of smoke, illuminated by lightning flashes, arose.

The following day, about 11 a. m., Sra. Cuara returned by the same path to see what had happened to her husband in San Nicolás. A small hill of stones of various sizes and of sand had formed about the vent where the smoke had first found exit. Some of the rocks hurled from the vent were very large and exploded in the air. She described

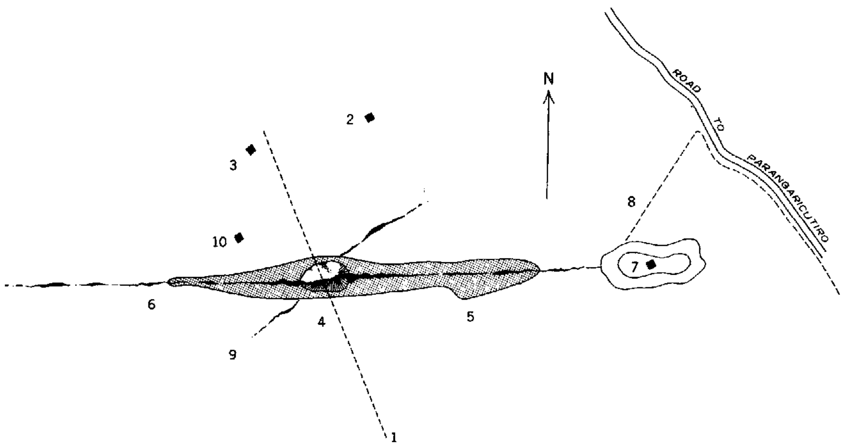


FIGURE 110.—Parícutin volcano at the time of its initial outbreak, showing the positions of the various features and eyewitnesses as seen by Sra. Aurora Cuara.

1. Direction of Toral's plowed furrow.
2. Position of Dionisio Pulido.
3. Position of Demetrio Toral.
4. Vent of the volcano.
5. Depression along the fissure.
6. The original fissure.
7. Piedra del Sol.
8. Path taken by Aurora Cuara.
9. A secondary crack of fissure.
10. Position of Paula Rangel de Pulido.

the little hill as round in form, and she could clearly see a fire, which she afterwards learned was lava, issue slowly from the bottom of it.

LUIS ORTIZ SOLORIO

Luis Ortíz Solorio was standing on the street corner near his house in San Juan Parangaricutiro talking to his neighbor the shoemaker. It was a quarter past 5 in the afternoon. Ten minutes later, looking toward Quitzocho, he saw a thin column of smoke arising. He went to the plaza, where many people were gathered in front of the church, for news had come that the earth had opened and smoke was issuing from a crack in the ground on Cuiyúsuru. The parish priest, Sr. José Caballero, with the permission of the presidente, Sr. Felipe Cuara Amezcua, decided to send a group of men to the spot to see what had taken place. Solorio offered to go and was joined by Jesús Anguiano, Juan Anguiano Espinosa, Epitacio Murillo, Hilario Anguiano, Epitacio Clasope, Justiniano Ciricuti, and some others whose names Solorio has now forgotten.

The priest first gave them his blessing, and they went on horseback, riding rapidly, and arrived at the spot at about 6 p. m. In the soil of Cuiyúsuru they saw a sort of fissure, at the southwest end of which was a hole about a half a meter in diameter from which smoke issued and some hot rocks were hurled not very high in the air. Juan Anguiano Espinosa and Jesús Martínez, in order to obtain a nearer view, approached close to the hole. Solorio then saw a fracture forming about 6 meters from the center of the vent and called to Espinosa and Martínez to come back. Hardly had they leapt back when the wall fell in, widening the orifice to 2 meters and increasing the size of the smoke column.

When they returned to San Juan Parangaricutiro, they related what they had seen, how the earth had opened and how smoke and small stones, like incandescent marbles and oranges were being cast out from a vent that continued growing bigger. The priest then consulted a book on Vesuvius in the church library, and they were convinced that they had seen a volcano.

ANGUIANO AND MARTINEZ

Juan Anguiano Espinosa and Jesús Martínez, both about 22 years old and of San Juan Parangaricutiro, were the first of the group leaving the plaza to arrive at Cuiyúsuru. They found the soil fissured in the form of a trench and saw a hole from whence smoke issued. Around the hole was a slumped area about 20 meters long and 12 meters wide, bounded by a crack along which were low mounds, one-half meter high, of very fine hot dust. This dust was gray, like ashes or cement; and Anguiano, wrapping a handkerchief about his hand, collected a sample of it to show in the village. From the vent itself fine dust, "sparks," and stones were thrown out. Anguiano and Martínez approached within a few meters of the vent, where a choking odor pervaded and the ground shook violently, "jumping up and down, not with the swaying motion we felt in Parangaricutiro." In the vent the sand "boiled" vigorously like the bubbling sand in a rising spring, with a noise like a large jug of water boiling violently, or boulders dragged along a stream bed by a river in flood. Small stones were cast up to a height of 5 meters. Anguiano collected two and found them very hot.[6]

The fissure in the soil extended in a direction toward the setting sun, that is, toward the point where Cerro de Canicjuata joins Mesa de Cocjarao, and the spring that supplied water to Parícutin. In the plan prepared for us by Anguiano, he indicated a small cross fissure, passing southwestward through the vent.

Anguiano modeled the appearance of the vent and its surroundings in the soil for us, a sketch of which is shown in figure 111.

In the plaza of San Juan Parangaricutiro the townspeople awaited their return with great anxiety. They related what they had seen, and Anguiano delivered the ashes and two bombs to the priest. The stones, being still hot, were placed in a dish; and the priest exorcised

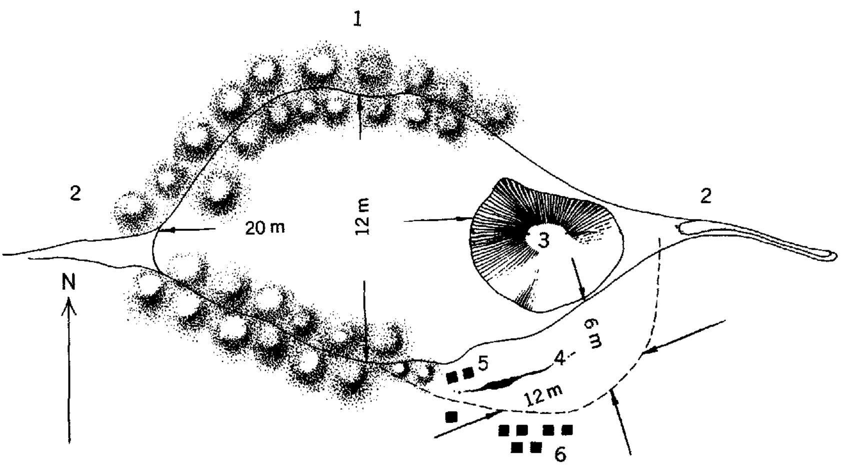


FIGURE 111.—Parícutin volcano at 6 p. m., February 20, 1943, showing the appearance of the vent and its surroundings as seen by Juan Anguiano E.

1. Small mounds of gray ash.
2. The fissure that opened.
3. The pit from which vapors issued.
4. The fracture that opened while Anguiano and Martínez watched the vent.
5. Anguiano and Martínez.
6. Other members of the Parangaricutiro party.

[6] These two bombs were later presented to us by the parish priest, Sr. José Caballero. One is now in the collection of the Instituto de Geología in Mexico, the other in the U. S. National Museum. The ash collected by Anguiano was presented to the Bishop of Zamora.

them, imploring Heaven to cease this terrible apparition, as a benediction and grace to the inhabitants of the region.

Anguiano added that for 14 hours before the outbreak of the volcano frequent tremors shook San Juan Parangaricutiro and the subterranean noises that accompanied these tremors seemed to come from Cerro de Jarátiro.

CELEDONIO GUTIÉRREZ

Celedonio Gutiérrez, of San Juan Parangaricutiro, was not an actual witness to the initial outbreak of the volcano but was in the town when the event occurred. Being an unusually keen and competent observer, his account of the first few days has more than ordinary value. Gutiérrez wrote for us the following account:

When I returned from my work in the fields, I saw a gray column of smoke arise from the place where the parcels of Quitzocho and Cuiyútziro [Cuiyúsuru] were located and that this column spread little by little. It was 4:30 o'clock in the afternoon of the 20th of February 1943. When I reached the church, I saw the presidente municipal, the parish priest, and many people gathered in the plaza. Quickly they ordered that a group of men go to investigate what it was that was burning. After a time the men returned saying that the earth had opened in Cuiyútziro, splitting it in the form of a crevise running from east to west, and that there, and from a hole that had also opened, fine sand and very hot stones issued, collecting in small mounds on both sides of the crevise and that they made a terrifying noise as they were ejected.

With the outbreak of the volcano, the earth tremors ceased, much to the relief of the populace. The priest and presidente allayed their fears somewhat, but on the morning of the 21st a strong earthquake threw them into panic, and they abandoned their homes; those from Parícutin fleeing to [San Juan] Parangaricutiro, those from Parangaricutiro to Angahuan or Uruapan, and those from Angahuan to the mountains.

The volcano broke out on Saturday, February 20, at about half past 4 in the afternoon. What a great surprise for my village and for the world! The earth was burned, and there began to ascend a small simple column that grew little by little; a vapor of strange gray rising silently toward the southeast. A little later many people came from Parícutin, which was nearest to the volcano. The presidente municipal, Don Felipe Cuara A., prepared to move the people from the place and had already asked, by means of telegraph, for trucks to transport all the people. But the people despaired and began to leave on foot, on horse, or on burros, or however they were able.

In the afternoon, when night began to fall, one could hear more noises. These we called rezaques.[7] Some tongues of flame began to appear, as of fire, that rose about 800 meters into the air, and others even higher that loosened a rain, as of artificial golden fire. At 8 or 9 at night, some flashes of lightning shot from the vent into the column of vapor. The column was now very dense and black and extended toward the south. It covered the grand mountain of Tancítaro, for the first sand and ashes were in this direction and cast the first cold shadow of the volcano over this area. From this hour the warming rays of the sun that warmed the mountains and the beautiful green fields ceased, and the green leaves

[7] Perhaps resacas, or surges, like surf upon a shore, is meant.

of the trees and the smaller plants that nourished the cattle died from the ashes that now began to appear. How strange and rare to see the clouds form, the first clouds of the volcano. Only a short time before the sky was blue, for the dry season had already begun. So, then, we passed the first night, contemplating and admiring this new event.

On the following day, Sunday the 21st, the dense vapors ceased. When the vapors diminished, the noise increased; and at 2 in the afternoon they were very strong. With each blast, white vapors accompanied by blue flames arose; the vapors appeared as if one shook a white sheet in the air.

After the first night, it threw up some tongues of fire, which were almost of pure sand. On the following night one noted that they were explosions of bombs and that the stones rose to a height of 500 meters. They flew through the air to fall 300–400 meters from the vent. It is a great memory for me to have seen, during these first days, how the first stones fell on the plowed fields of Quitzocho, where I used to watch the cattle of my grandfather.

At 3 o'clock on the morning of Monday, the 22d, there were earthquakes like we never had before. The earth shook for 7 or 8 minutes, with intervals of a few seconds. The people imagined that this was the ultimate agony of a great region. Who could check the great movement of an entire region? [8] Only the omnipotent God, in his great power, with his divine omnipotence, thought of us. It was He who saved us.

The first lava that the volcano gave forth, to the east of the little cone, flowed 3 meters per hour, according to the data of Sr. Geologist don Ezequiel Ordónez, who was sent by the Comisión Impulsora y Coordinadora de la Investigación Científica, México, D. F., to observe this important novelty. This gentleman, 78 years of age, through his studies and experience, convinced us that there was no danger to our village and counseled that the people return to their homes. Now this same gentleman showed us the first lava flow, moving like dough, from which fell incandescent rocks from one side or another, such rocks as we knew before, without knowing how they formed. We also saw the malpais, which we knew before, without an idea of its origin. Without doubt, this answers not only how the malpais formed but also the tillable land and the mountains that I knew. We saw the lava as it covered the cruza [9] made by the yokes of oxen from Parícutin and which needed only 8 days for sowing. Now one sees an admirable flow of fire, covering the last traces of our footsteps and of the works of man that he made during the life that God permitted him.

RECORD OF SAN JUAN PARANGARICUTIRO

Sr. Felipe Cuara Amezcua, presidente of the municipio of San Juan Parangaricutiro, has provided us with a certified copy of the record of the meeting of the municipal council signed by the council members, which is, as far as the municipal records are concerned, the official history of this unusual event. A translation of this document follows:

In the village of [San Juan] Parangaricutiro, seat of the municipality of the same name, State of Michoacán de Ocampo, at 10 o'clock on the 21st day of the month of February 1943, gathered in the public hall of the municipal government, under urgent summons, the councilmen: Felipe Cuara Amezcua, municipal mayor; Félix Anducho, trustee; Rafael Ortiz Enriques; Ambrosio Soto; and Rutilio Sandoval; as well as Agustín Sánchez, resident of said place. The Regidor, Felipe

[8] This earthquake had its epicenter in the sea, near Acapulco, and was not directly related to the volcano.
[9] Second plowing in preparation for the sowing.

Cuara Amezcua, President, declared the session opened, stating that yesterday at about 6 p. m., Messrs. Sánchez and Pulido presented themselves, telling, greatly excited, of the appearance of a strange conflagration that occurred at 5 p. m. yesterday in the valley called Cuiyútziro [Cuiyúsuru], to the east of the village of Parícutin. They asked that they be taken immediately to the place of the happening that one could see for oneself the truth of their assertion; at the time Dionisio Pulido, owner of the above-mentioned property, gave the information that early on the day of the event, he left his village [Parícutin] to tend his sheep in company with his wife Paula Rangel de Pulido and to visit his properties situated in the said valley; that in the afternoon, at an early hour, he left the place, asking his wife to watch the sheep until he returned; that about 4 p. m. he returned to the place and asked Demetrio Torres [Demetrio Toral] who worked in the fields, to unyoke the oxen and take them to water, after which he returned to his wife suggesting that she return to the village, going then to examine the work done in the fields, arriving at the slope of the nearby hill to the east; that there, about 5 p. m., he felt a strong tremor and din in the earth, to which he paid little attention, since seisms had been frequent for more than 8 days, but he continued hearing loud subterranean noises accompanying the tremors, and then, thoroughly frightened, he turned his gaze to the west, that is, toward his village, observing with surprise that down there in a depression long tongues of fire arose, with a great deal of smoke and noises never heard before. A terrible panic seized him, and he fled toward Parícutin, where he arrived out of breath, immediately recounting to C. Agustín Sánchez, chief of the Parícutin subdivision, what had occurred. That Señor Sánchez, convincing himself of the truth of what Pulido had told him, went with him to the municipal president of Parangaricutiro where, totally alarmed, they gave the facts to C. Felipe Cuara Amezcua, who with the haste the case merited, went with the informants to the place where the phenomenon had appeared, and later they learned that it was a volcano. Returning to Parangaricutiro, the municipal president summoned the members of the council to attend the present extraordinary session and consider this matter, now that the fear has extended to all the nearby villages, and solicit, for this reason, ample powers from the council to act; he gave as important in the case that now the volcano grew with real fury and, with it, the panic of the inhabitants of the region who abandoned their homes and possessions. It was conceded at once to C. Felipe Cuara Amezcua, who immediately began action to solve the problem in the best manner, soliciting by telephone and telegraph the help of General of Division, don Manuel Avila Camacho, Constitutional President of the Republic; General of Division, don Lázaro Cárdenas, Secretary of National Defense; of General Félix Ireta Vivieros, Governor of the State; the Department of Agriculture and Government; municipal authorities of Uruapan; and other official agencies. Upon the proposal of some residents of this place and of Parícutin, the correct name that the mentioned volcano should bear was discussed, and after ample deliberation, in which was taken into account the history, traditions, and desires of the people, it was unanimously denominated "Volcán de Parícutin."

SUMMARY OF ACCOUNTS

After a fortnight of subterranean noises and local earthquakes that appeared to center between Cerro de Jarátiro and Cerro Prieto, lying to the southeast of Parícutin village, and which continually increased in number and intensity, a small fissure appeared in the soil of the cultivated lands of Cuiyúsuru farm. This fissure, beginning near

Piedra de Sol, extended westward toward a point where Cerro de Canicjuata joins Mesa de Cocjarao and passed through a small cave or sink on Cuiyúsuru farm. The fissure had an observed length of about 50 meters, a width of 5 centimeters, and an apparent depth of only ½ meter. A small subsidiary fissure having a southwest direction also formed. The evidence suggests that the fissure opened during the afternoon of February 20, probably about 4 o'clock, or half an hour before the initial outbreak of the volcano. At about 4:30 p. m. at a point on the fissure sulfurous gases and steam were emitted with a pop, followed by a whistling noise; and a small eruptive column arose from the newly formed vent.

The vent was originally of small size, about 30 centimeters in diameter, according to Paula Pulido; and the eruptive column consisted of fine dust and small incandescent stones. The vent gradually widened by slumping of its walls, and the eruptive column gradually increased in size (pl. 16*A*, *B*). Ejected stones collected during this period consisted of fragments of basalt different in character from Parícutin lava, and probably represent the walls of the fissure. (See table 2.)

Some time between 11 and 12 p. m. the activity of the new volcano became violent; incandescent rocks were violently ejected in great numbers, and a large eruptive column, accompanied by frequent lightning flashes and a tremendous roaring sound, arose from the newly formed vent. This change in activity suggests that the advancing gases of the initial phase were followed by the rising lava column and that it reached the surface at this time.

DEVELOPMENT OF PARÍCUTIN VOLCANO

After the initial outbreak of Parícutin volcano on February 20, 1943, 2½ years were to pass before it became apparent that the new volcano had acquired a definite pattern of activity and that the volcano could be considered a well-established and mature volcanic edifice. This interval of development may be divided into three periods, depending primarily upon the vent with which the principal activity was associated. These we propose to call the Quitzocho, Sapichu, and Taquí periods.

The first, or Quitzocho period, endured from February 20 to October 19, 1943. The activity was centered exclusively in the original Cuiyúsuru vent, about which the volcano built its cone. The important feature during this period was the growing cone and the accidents that befell it. At the end of this period the cone had almost reached its full height, or about 365 meters, and had acquired a considerable degree of stability.

This period was to terminate suddenly with the outbreak of new vents, the Sapichu vents, at the northeast foot of the cone.

The Sapichu period, covering the activity of the Sapichu vents, lasted from October 19, 1943, to January 8, 1944. A small adventitious horseshoe-shaped edifice, called Sapichu, was built about this vent; but the principal feature was the almost constant emission of lava to form a broad flow. During the Sapichu period, activity in the Cuiyúsuru vent (the main crater) was greatly reduced, and no significant changes took place in the main cone.

With cessation of lava emission from Sapichu, activity shifted to two vents, the Taquí and Ahuán, on the west and south sides of the cone respectively. A period of almost continuous extravasation of lava set in, during which the cone showed erratic and variable activity but no significant change in configuration. This period we have called the Taquí period.

The account that follows will be considered according to these three periods: Quitzocho period, building of the cone; Sapichu period, eruption of the adventitious cone Sapichu; Taquí period, lava flows.

QUITZOCHO PERIOD

EARLY EXPLOSIVE PHASE

February 21.—One may consider the Quitzocho period of Parícutin volcano as beginning at midnight, February 20. The vent now had 7 hours of development, and the first small beginning of the cone became apparent. At midnight, February 20, the cone was 6 meters high and elongate in form, with its long axis east and west (Robles Ramos, 1943). About this time the first thunderous roars were heard in San Juan Parangaricutiro. The earth tremors that were felt during the past fortnight now ceased and were not felt again. At 4 a. m. February 21, the cone was estimated as being 8 meters high. Dionisio Pulido visited his farm at 8 a. m. and reported the cone as 10 to 12 meters high. Mauricio Duarte estimated the height as 25 meters at 10 a. m. and that the column rose higher than Cerros de Tancítaro. Jorge Treviño described the volcano as a low cone with an oval crater at 11 a. m., from which arose a black eruptive column accompanied by strong explosive blasts. Sra. Aurora Cuara, who passed the volcano at 11 a. m., described it as a small round hill of stones, from which rocks were hurled into the air. From the bottom of this hill a "fire" slowly issued. Between 12 m. and 1 p. m. the volcano began again to eject many bombs, the bursts spreading in the form of a fan and dropping bombs in a wide east–west zone. At 1 p. m. the cone was estimated as 30 meters high, with a base 70 meters in diameter. Jorge Treviño estimated that on this afternoon the cone was 50 meters high. Celedonio Gutiérrez reported that the eruptive column diminished in size during the early part of the day and that the ejectamenta changed from ash to bombs accompanied by white vapors and blue flames. These bombs were hurled to a height of 500 meters, some falling 300 to 400 meters from the cone.

Photographs of the volcano by Dr. J. Trinidad and Salvador Ceja (pl. 17*A*) and motion pictures by Jorge Treviño show the cone as a low dome, with slope angles of 32° toward the west but more gently inclined toward the east. This asymmetry of the cone indicates that it had already been breached and that lava had already flowed toward the east. The eruptive column, as shown by motion pictures, rose rather lazily without well-defined volutes or cauliflowers. Large tatters of lava up to a meter across were ejected in abundance. According to Celedonio Gutiérrez, these had imitative shapes, resembling birds and objects, indicating that they were still plastic. At least two neighboring vents were present in the crater. The western vent appeared more active and its column more heavily laden with ash; the eastern vent was erratic in its action and appeared to be somewhat smaller than the western vent. The eastern vent ejected more large bombs and coarser material than the western vent.

The eruptive activity of February 21 is described by Celedonio Gutiérrez (personal communication) as follows:

> On this day, which was Sunday, between one o'clock in the morning and until 12 o'clock, the eruption of the volcano did not vary much from that of late yesterday. The eruptive column was like that previously observed, rising towards the heavens in large agitated cauliflowers, which left the crater with great force, and from which fell much ash and many bombs. The only difference noted was that now one saw no electrical discharges.
>
> Between 12 and 13 o'clock the volume of ejected material began to diminish and ash ceased to fall. Bombs continued to be thrown out but in less quantity, and there began deep, heavy, thunderous noises, increasing in intensity.
>
> Between 13 and 15 o'clock the explosions increased in both force and frequency; the amount of material, however, diminishing each time but the fear of the people of San Juan [Parangaricutiro] increased. One could see with each explosion in the volcanic vent small white clouds of smoke arise with great force, like from the mouth of a cannon. The explosions were extraordinarily violent, greater than cannonading.
>
> From 15 o'clock until 3 o'clock [February 22] the form and type of the explosions showed no change.

Other observers described the cone as having a horseshoe form, open toward the northeast. The dark-gray eruptive column rose to a great height and was accompanied by many bombs, some of them of great size, and a sort of coarse sand. The eruption seemed to issue from a long opening, in the form of a fissure, westward toward Mesa de Cocjarao. From the ground it was impossible to determine accurately the number of eruptive throats, but it appeared to have but one, large and somewhat elongated.

These inconsistent descriptions of the cone and its activity suggest that the eruption was quite variable.

It is likely the lava first issued from the surface vents sometime during this day. What apparently was lava was observed by Sra. Cuara at 11 o'clock. The great quantity of viscous bombs indicates that the rising lava column had already reached the surface, and the horseshoe shape of the cone suggests that the weak cone had been breached by flowing lava. Perhaps the rising lava column first reached the surface at midnight of February 20, when the first thunderous roars were heard in San Juan Parangaricutiro and incandescent rocks were hurled up with great force.

February 22.—Mr. C. Byron Valle, who flew over the volcano on the early morning of this day, reported that he distinctly saw two vents in the crater. A smaller one, at the base of the cone, did not have much explosive force; and lava appeared to issue from it. A larger vent showed only explosive activity. At the altitude of the plane, a distinct sulfurous odor was apparent, which Mr. Valle characterized as an odor similar to that about a smelter.

Celedonio Gutiérrez reported that at 3 a. m. a strong earthquake, stronger than any yet felt, shook the region intermittently for 7 or 8 minutes. This earthquake was felt over a wide area in Mexico, and its epicenter was determined to be off the coast near Acapulco, a spot of frequent heavy earthquakes. It therefore had no direct connection with Parícutin volcano.

Celedonio Gutiérrez in his diary described the activity for this day as follows:

> Between 2 and 3 o'clock, after a terrible night occasioned by the tremendous noise of the volcano, strong earthquake shocks were felt, much greater than those felt before the birth of the volcano, which lasted for 8 seconds. After the earthquake the terrible explosions of the volcano began to diminish little by little, but did not cease. Although the thunderous noises were now not so strong, the eruption could not by any means be called silent. Ash fell in moderate quantity but, in contrast, bombs were ejected in great quantities and arose to an elevation of about 400–500 meters. The eruptive column that arose from the crater was not very large but it rose to an elevation of about 1,500 meters.

Photographs by Rufus C. Morrow (pl. 17*B*) taken on this day show an irregularly shaped cone, open to the east indicating breaching by flowing lava. The eruptive column was larger and denser than on the preceding day and contained a very large quantity of large bombs.

The already well advanced lava flow formed an irregular tongue that moved northeastward, emitting abundant white vapors from scattered fumaroles along an advancing flow front 6–8 meters high. At no later time did this or any other lava flow show such an abundance of vaporous emissions. This first lava flow we have called the Quitzocho flow. The shape and character of the eruptive column suggest numerous and violent explosions in the crater. Celedonio Gutiérrez reported explosions each 10–12 seconds and that the ejected bombs assumed odd shapes, such as heads, hands, and feet, indicating that they were tatters of viscous lava.

February 23.—Eruptive activity continued with the abundant emission of bombs but with little ash. Ordóñez reported the cone had a height of about 60 meters (pl. 18*B*) and that the lava advanced at a rate of 6–12 meters per hour.

February 24.—The activity of the crater continued in a regular fashion, with many bombs ejected but with little ash deposited on the fields. The lava flowed as a broad sheet, 700 meters long (Waitz, 1943) and advanced 5 meters per hour. A blanket of fragments and scoria covered the lava surface. The emission of vapors from the flow appeared greatly diminished and localized in fumaroles along the border of the flow (pl. 18*A*).

February 25.—The activity from the crater continued strongly but with somewhat better defined cauliflowers and thicker eruptive column, indicating somewhat increased activity. According to Waitz and Ramiro Robles, the explosive bursts averaged 16 per minute. These Ramiro Robles classified as 6 blasts, 9 explosions and 1 lightning discharge per minute. De la O Carreño noted 20 explosions per minute and Teodoro Flores, 17 explosions per minute, 3 strong, 5 medium, 9 weak. Waitz reported that the breach, which had been kept clear by the constant flow of lava, now showed some signs of building up, indicating a cessation of flow from the vent, and that the advance of the lava was reduced to 3 meters per hour.

February 26.—On this day the height of the cone was measured by Ramiro Robles (1943) as being 167 meters, with diameter of the base 730 meters and the diameter of the crater 90 meters across in a north-south direction.

With the cessation of the lava flow the day before, the explosive activity in the crater had increased. A medium-sized black eruptive column arose majestically to a height of about 5,000 meters and terminated in a broad, white cumulus cloud. Some heavy explosive bursts ejected heavily laden clouds, the ash raining down upon the cone. At 2 p. m. a wet ash fell, the moisture probably due to the condensation of water vapor in the eruptive column. De la O Carreño reported that on many occasions the granules of ash were coated with a thin film of water.

Waitz, Ramiro Robles, and De la O Carreño distinguished three types of explosions: (1) blasts, (2) gaseous explosions, and (3) electrical discharges. The blasts were dull prolonged roars, like a jet produced by a piston in a steam engine, and yielded a vertical column of vapors heavily laden with ash, and carrying few bombs. The duration of these blasts varied, sometimes continuing for 6 minutes. When these blasts were numerous and prolonged, the explosive activity was cineritic. The gaseous explosions were violent expulsions of gas, with strong detonations, giving rise to cauliflowers. They were accompanied by innumerable quantities of bombs, hurled as high as 750 meters and thrown as far as 900 meters from the cone. The electrical discharges were vigorous detonations without eruptive phenomena. The visible flashes were short zigzag or arborescent bolts of lightning in the cineritic eruptive column.

Observers noted rapidly moving arcs of light in the eruptive column, followed by extremely heavy explosions. The arcs were described by De la O Carreño as an intensely luminous yellow band and by Ramiro Robles as whitish yellow. Waitz identified these flashes as the "flashing arcs" of Perret (1912). These arcs were plainly visible in daylight.

By this day the lava flow had spread over a considerable area and formed a mass of irregular outline, the narrowest part 464 meters wide. It had a steep front, 5–11 meters high, and an irregular surface covered with a jumble of scoriaceous blocks of irregular shape. The lava front was loose rubble with sporadic exposures of torn and twisted lava. During the day, red incandescence could be seen in the crevasses of the lava front, and at night patches of bright incandescence marked the slowly advancing lobes of viscous lava. The rate of advance was now reduced to 1–2 meters per hour. As the flow advanced it frequently piled up a bank of soil along its foot. De la O Carreño (1943) gave the following statistics for the cone on this day: Elevation of the cone 167 meters, diameter of the base of the cone 615 meters, diameter across the crater 150 meters, slope of the cone 33° 10′, approximate volume of the cone 19.5 million cubic meters, daily increment (5.9 days) 3.33 million cubic meters, explosions per minute 17, increment of growth per explosion 136 cubic meters, volume of the lava flow 7 million cubic meters.

For the last 4 days of February, Robles Ramos (1943) gave the explosive activity as follows:

February 25. 16 explosions per minute: 6 blasts, 9 explosions, 1 electrical discharge.
February 26. 18 explosions per minute: 9 blasts, 6 explosions, 3 electrical discharges.
February 27. 15 explosions per minute: 10 blasts, 4 explosions, 1 electrical discharge.
February 28. 15 explosions per minute: 11 blasts, 4 explosions, occasional electrical discharge.

Many visitors came to the volcano during this period, attracted by the awesome spectacle of its explosive activity. At night the appearance of the volcano was particularly impressive. Innumerable incandescent bombs formed an almost continuously rising column of "fire" that ascended to 750 meters and then rained down upon the cone and the surrounding terrain. This incandescent column illuminated the area with a weird light, brighter than moonlight. The thunderous roars and rushing blasts, punctuated by the sharp crack of explosions, the thud of the bombs upon the flanks of the cone, the lightning discharges, the strong vibrations of the air and ground, held the spectator in awed fascination.

TABLE 3.—*Summary of the first week of activity*

Date	Time	Height of cone (in meters)	Lava activity	Crater activity
Feb. 20	12:00 p. m	[1] 6	None	Cineritic, medium.
21	4:00 a. m	[2] 8	do	Do.
	6:00 a. m	[3] 8	do	Do.
	10:00 a. m	[4] 25	do	Do.
	11:00 a. m	[5] 6–7	Slow (?)	Do.
	12:00 a. m		None	Bombs, heavy.
	1:00 p. m	[2] 30	do	Do.
	3:00 p. m	[6] 30	do	Do.
		[7] 30–50	do	Do.
22			Rapid flow	Do.
23		[8] 60	6–12 m/hr	Do.
24			5 m/hr	Mixed, heavy.
25			3 m/hr	Do.
26	2:00 p. m	[9] 165		Do.
	4:00 p. m	[10] 167	1–2 m/hr	Do.

[1] De la O Carreño, Alfonso, [quoting Jesús Mungía] (1943).
[2] Robles Ramos, Ramiro (1943).
[3] Pulido, Dionisio, personal communication.
[4] Duarte, Mauricio, personal communication.
[5] Waitz, Paul (1943).
[6] De la O Carreño, Alfonso, quoting Sr. Cuara (1943).
[7] Treviño, Jorge, personal communication.
[8] Ordoñez, Ezequiel (1943).
[9] De la O Carreño (1943).
[10] Robles Ramos, Ramiro (1943).

The first day of the new volcano saw the first surge of lava, which spread rapidly at first but gradually diminished its rate of advance until the seventh day when it stopped, and showed a tendency for the cone to heal its breach. On February 28, however, a second lava surge began, which cleared the breach. From the east the crater had the appearance of a low amphitheater with three active vents plainly visible. The lowest, and easternmost, was the smallest and the westernmost, the largest and highest; all were separated from each other by narrow septa joined to the inner crater walls. Usually these vents acted independently of each other, although they were sometimes active simultaneously.

The lava flowed from the amphitheater toward the east; but upon clearing the flanking wall of the cone, it turned north and moved down the slope as a scoria covered flow, covering the lands of Quitzocho.

Activity in the crater appears to have been rather erratic, varying from heavy cauliflower bursts to brief periods of inactivity. Explosions were reduced to 14 per minute, more than one-half of them being blasts.

The activity on February 28 has been described by Parker D. Trask (1943). The ejectamenta consisted of viscous lava bombs and coarse ash. The smoke column was relatively thin, consisting of isolated cauliflower bursts, strung together in a vertical column. The explosive bursts had the appearance of originating at the throat of the vent, or only a very short distance below. Explosions occurred at fairly regular intervals of about 4 seconds; sometimes explosions came in rapid succession, sometimes at intervals of 6 to 8 seconds. The explosions, in general, had their origin at the vent, although there were some in the ash cloud, 150 meters above the summit of the cone (lightning?). Large bombs were hurled to a height of 120 to 250 meters. The greater part of the material ejected at this stage consisted of bombs rather than of ash or sand. Each explosion threw bombs 600–900 meters into the air. Most of them fell upon the cone. The greatest distance from the cone that bombs were found was 1,000 meters from the center of the volcano. The bombs rose so high that many of them took 12 to 15 seconds to fall back to the crater rim, 500–1,000 meters below. They were roughly spherical, and their size ranged from that of "a nut to that of a house," but most of them ranged from 1 to 2 meters in diameter. The largest block Trask saw was 50 feet (15 meters) in diameter and was hurled 300 feet (90 meters) above the summit of the crater, that is, 850 feet (260 meters) above the vent. Almost all the bombs were entirely solid when they fell, for they did not change their form upon impact. The lava flowed at a rate of 3 feet (1 meter) per hour toward the west and spread laterally at a rate of 1 foot (⅓ meter) per hour.

The activity of the volcano for the period February 25 to March 5 has been described by Teodoro Flores (1945), a translation of which is given below:

THE CRATER

On February 25 the crater of the volcano was situated toward the west border of the cone, with a form almost circular, whose dimension was estimated at 50 meters. In one aspect the cavity was similar to a funnel, with a slight sag in its rim that coincides in position with the northeast opening. It remained in this place and unchanged in form, other than an amplification of the crater each day, during the 26th and 27th.

On February 28 there began the development of a sag on the northwest [10] side of the crater, resulting in an undulating form of the rim; at the same time one noted that the crater showed a movement, tending to shift to the east. The sag deepened during the night of the 28th; and on the following day, March 1, it was perfectly visible, measuring then about 30 meters deep. The side continued to slump during the day, and at 6 p. m. viscous lava began to flow slowly from it along a wide and shallow break that had formed in the northwest [11] flank of the cone and extended from the rim of the crater almost to the base of the volcano.

On March 2 the crater had deeply destroyed its northwest [12] wall; and the vent emitted great quantities of lava fragments toward the hollow left by the primitive vent, which rapidly filled. Furthermore, one could perceive clearly that a smaller vent had opened on the northeast side, from which gases and igneous materials escaped that were expelled either simultaneously or alternately with the other vent.

Examining the crater the same day from the northeast, in the direction of the opening of the cone, one could clearly distinguish the two vents, the eastern one being lower and smaller than the western; and it could be observed as well that both vents were localized very close to the highest point of the crater rim.

At 7:30 p. m. of the same day, both vents were very active; and a great quantity of lava flowed from a mound situated in the bottom of the northeast opening, advancing rapidly and invading the fields situated in front of the opening.

On March 3 the primitive vent and the break that had formed on the northwest [13] slope of the cone were filled with igneous material, completely restoring this part of the rim of the crater to its previous outline. In the early morning of this day I had occasion to observe the projection of a column of incandescent lava in the form of an enormous fountain that issued from the medium slope of the volcano.

On March 4 the crater and its two vents presented an aspect very similar to that of the day before, but one noticed that they were a little lower in elevation. The vents were further lowered on the 5th, with the result that the existence of another vent, clearly circular in form, could be perceived below the second vent (pl. 19*A*).

These changes are clearly shown in the illustrations that accompany Flores' report.

Explosions continued during the early days of March, sometimes so strongly that windows in San Juan Parangaricutiro rattled and doors swung open and shut with each explosion. Not only were the explosions heard in the town, but the blasts were distinctly felt. The eruptive activity continued to increase each day, but with rare brief intervals when the crater was silent. Activity and the shape of the cone remained essentially unchanged until March 18.

The Quitzocho flow issued directly from the explosive vent of the crater (pl. 20*A*). Its steep rubbly front advanced slowly, but little

[10] This is an error; the true direction was northeast.
[11] Idem.
[12] Idem.
[13] Idem.

flowing lava was discernible. By the end of March it had spread over the entire Llano de Quitzocho to the western slope of Cerro de Jarátiro ridge.

The first advance of the Quitzocho flow, which began sometime during February 21, must have been rapid for it had already covered an extensive area when it was first recognized as a lava flow by Ordóñez. It soon slackened its pace, however, the moving fronts advancing at rates varying from 1 to 2 meters per hour during its first week, later slowing to a rate of only several meters per day. At least two surges were recognizable, one terminating on February 26, the second beginning on February 28 and continuing until March 20.

The flow spread out in a great sheet with a front ranging from 6 to 15 meters high. The surface of the flow, after it came to complete rest, was undulating and very hummocky, sloping at a declivity of about 5° from the foot of the cone to the north (pl. 19*A*). The elevation of some of the higher hummocks and ridges sometimes exceeded 5 meters. The eastern front of the flow was made up largely of a blanket of loose scoriaceous blocks and sandlike, granular, disintegrated lava, with scattered excrescences of massive fissured or twisted lava. The exposures of fractured lava frequently showed a bright incandescence in fissures and were the loci of fumaroles. The lava front facing Cerro de Jarátiro ridge had a somewhat different aspect. It was higher, reaching 15 meters in elevation, and extremely rugged, with huge blocks of torn or disintegrated lava rising in irregular pinnacles or forming cockscomb ridges. Fumarolic activity was particularly evident along this front. Two steeply conical peaks situated about 100 meters from the northeast base of the cone and rising about 7 meters above the general surface level were prominent features of the lava surface that caught one's eye. While having some resemblance to eruptive cones, the peaks showed no evidence of eruptive activity and probably resulted from pressure.

One of the features that distinguished the Quitzocho flow from later flows was the apparently high content of volatile constituents, as manifested by its abundant fumaroles. These fumaroles, however, were not generally distributed through the flow but localized along its peripheral portions (pl. 19*B*), usually along the front face at the crest of the front (pl. 21*B*) or in a zone less than 50 meters back from the crest. A few weak fumaroles at the summits of conical knolls were situated on the lava mesa itself.

On March 20 the cone began to heal its breach, indicating that the Quitzocho flow had ceased, and no further emissions of lava took place at this point. The flow already extravasated, however, continued to spread in all directions (pl. 20*B*).

During the period of the Quitzocho flow the explosive activity was, in general, moderate (compared with later activity) although the accompanying noises were terrific. The ejected material consisted principally of bombs, largely semifluid in character, indicating that the explosions took place at or near the surface in a rising column of liquid lava. The cone grew rapidly, but the spread of ash over the surrounding terrain was comparatively slight.

The cone frequently changed its configuration during this period, owing in part to the varying activity or shifting of the three vents, but chiefly owing to the erratic flow of the lava. During pauses in the emission of lava, the wall of the volcano was built up by the accumulation of ejected bombs, only to be breached again by a new lava surge. The volcano showed alternatingly a conical form or a horseshoe shape. The original small mound, roughly conical, changed to a horseshoe shape with the first extravasation of lava. From February 21 to 25, it remained in this form, becoming cone shaped again for a brief period, February 26 to 27, only to be breached again on February 28. This breach was finally restored on March 20. The cone thereafter, as will appear later, attained such proportions that lava flows were no longer able to breach the cone completely.

HEAVY CINERITIC PHASE

On March 18 the heavy bomb stage ceased; the crater passed into a very heavy cineritic phase which continued with some variation until early June. It was during this period that the greatest ash damage to the surrounding countryside was done. A huge column of ash and vapors boiled violently from the volcano in turbulent cauliflowers. Frequently they completely filled the crater from rim to rim, rising as a majestic eruptive column to a height of 6 kilometers or more.

The cineritic phase began on March 18 and continued all day with gradually increasing intensity until, in the night, the activity changed to a dense, billowing black eruptive column, and great "flames" or fountains of incandescent bombs rose to a considerable height. The number of heavy explosions increased; a deep roar seemed to come from the depths of the earth, and the ground shook under apparently ceaseless shocks. The fury of this night exceeded anything hitherto experienced at Parícutin and filled the observers with alarm, but by morning the violence diminished, and the noise changed to a continuous low rumble. The crater of the cone now appeared considerably enlarged, and a dense black, heavily ash-laden column rose in majestic volutes high into the atmosphere (pl. 21*A*). The winds, which at this season prevail from the west and southwest, carried the fine ash far to the east. Some ash had previously fallen on the region, but its distribution was very local; even in the immediate environs of the cone it was not more than a few centimeters thick. From March 18 to June 9, however, the ash fall was by far the heaviest experienced in the history of Parícutin. The ash cloud hung like a black pall over the region to the east and northeast so that the day was like dusk. A smoky haze dimmed the light of the sun as far east as Toluca, and fine ash fell on the rooftops and streets of Pátzcuaro, Morelia, and Zacapu, and even as far as the Bajio 250 kilometers away. The Carapan–Uruapan highway was covered with a thin mantle of ash, which swirled about and drifted into small windrows like dry snow. The fields and forests took on a dusty dark hue. Nearer the volcano the ash sifted through the trees of the forest with a gentle rustle like falling hail and blocked the Uruapan–Parícutin road. Figures passing but a few yards away appeared eerie and ghostlike in the ashy haze. Even at a distance of several kilometers, vesicular fragments as much as an inch across drifted down. On March 27, 15 centimeters of ash fell at a point 6 kilometers to the east of the cone. During early May the ash fall at Uruapan became so heavy that it was necessary to clear the roofs of the houses; it filled the patios to a depth of a few centimeters and all but halted motorcar traffic in streets. With the coming of the June rains, much of this ash was washed from the slopes of the hills, almost completely filling some of the small steep-walled arroyos, and in time the ash blanket over the fields and in the forest became so completely blended with the soil that it was no longer apparent over much of the area originally covered.

During April, May (pl. 22*B*), and early June, the eruption continued as a magnificent vertical column rising in volutes to a tremendous height. From angle measurements taken from Uruapan, we calculated its altitude as 6,000 meters above the crater. The black lower portion of the eruptive column (it appeared plum colored from a distance) passed through successively paler stages to a huge spreading white cumulus cloud. The prevailing winds carried the column toward the south, where it formed a dark curtain of settling ash. During this period the early morning hours were clear and bright; but as the rainy season approached, wisps of clouds began to appear about 9 o'clock, the first ones forming in and about the drifting ash curtain (pl. 23*A*).

The rains began in May. Heavy showers accompanied by thunder frequently began about 2 p. m. and continued intermittently, and commonly very locally, until 4 or 5 p. m., when the weather cleared again. During the rainy part of the day the condensed water vapor from the fumaroles of the Quitzocho lava flow increased. The rising wisps of vapor from the fumarole vents clung lazily to the slopes of the lava front and were drawn toward the cone from all directions. Towards nightfall, the vapors frequently collected as a blanket around the base of the cone. The first rains had little erosive effect upon the cone. Narrow radial lines of steam streaked the cone; or if the rain was heavy and driving, a whole sector of the cone gave off steam which disappeared very soon after the cessation of the downpour. Beneath the drifting ash column, a fall of mud was not infrequent.

During this period the surface winds were from the west, but the higher winds carried the ash curtain toward the south. Bombs of the larger sizes fell upon the cone or on the fields and in the forests for a radius of about 1,000 meters about the cone. Bombs found in the woods some distance from the cone were frequently as much as a meter or more in diameter. They fell in such numbers that it was impossible to approach the base of the volcano. The temperature of the air was distinctly cooler in the falling ash or lapilli beyond the zone of bombs than outside an ash fall. Small lapilli were distinctly cold to the touch. It was not until the falling lapilli reached about 3 centimeters in size that they showed perceptible warmth. The bombs showed no incandescence on the surface during the daytime, but were bright red or orange in cracks or when broken open. Although incandescent inside, the surface temperature of one small bomb that fell close to us was 202° C immediately after its flight. In the area south of the cone, domes of ash 1½ meters high collected beneath the wide, spreading oak trees, their branches intercepting much ash and finer lapilli. On May 24 we went to Taco's house, about 1½ kilometers south of the cone, and found only the ridgepole above the ash, indicating that during 2 months of ash activity the depth of accumulated material at this place had reached about 2 meters. All through the forest, the pine trees were buried above their lower branches (pl. 34*A*).

At about 8 p. m., March 18, the noises of the crater began to diminish; at the same time the eruptive column increased and became heavily laden with ash. The cone was now so silent that the inhabitants of the region believed that the volcano would cease or change to some new activity. Not a visible bomb rose about the crater rim. Now a second vent opened on the south side of the cone, and lava flowed in two streams toward the southwest. The area lying between the cone and lowest slopes of Cerros de Tancítaro had many cañadas, small basins, and small mesas; and the new flow filled some of the larger basins. The flow was short and was soon covered and hidden by heavy ash falls. Its lava differed from that of the Quitzocho flow in being more blocky and more heavily oxidized, red or cinnamon. Unfortunately, no record was made of its particular characteristics nor the extent of its fumarole emissions. This flow we have called the Pastoriu flow.

During most of April 17, the heavy ash column continued as previously, but at 3:30 p. m. activity again ceased, and the eruptive column

338669 O—55——4

died down completely About a quarter of an hour later eruptive activity resumed, but with much less ash and many bombs, accompanied by deep grating roars. With this change in explosive activity, a second lava flow broke out from the same vent from which the Pastoriu flow had issued; the new flow carried with it a large portion of the south side of the cone, which formed a ridge, 60 or more meters high, moving slowly toward the southwest The ridge broke into two wings. The eastern segment, swinging on a pivot at its contact with the cone, appeared to be an intact section of the cone. The western segment moved out farther than the eastern wing and was more disturbed. These two segments and the concave slope of the broken cone formed an amphitheater. The lava flow, issuing from the base of the cone, passed between the two wings of the break and flowed down a small cañada, following the trail from Cerro de Chanamuro to Parícutin. It continued as a small flow about 20 meters wide, followed the southwest and west base of the cone, and spread out over the Llano de Quitzocho to the now immobile Quitzocho flow. Then spreading westward, it advanced to the narrow valley separating the Cerro de Jarâtiro from the lower slopes of Cerro de Canicjuata. This lava front still showed some slight advance on March 23 but ceased almost immediately after. The junction of the Quitzocho lava and this flow formed a rugged V-shaped valley extending from the foot of Cerro de Jarâtiro to the base of the cone, and along this junction of the two flows fumarolic activity was particularly abundant. The front of the flow was unusually asperous, contrasting distinctly with the already ash-covered Quitzocho flow; jagged pinnacles of tilted lava blocks projecting from a front of blocky rubble gave it a particularly rugged appearance. This flow was typical block lava (pl. 21*B*). We have called it the Mesa del Corral flow.

With the outbreak of the Mesa del Corral flow, the crater resumed its heavy cineritic stage. The heavy ash falls of this period soon repaired the break of the cone and covered the flow, but its effect was evident for some months afterward as a high half-domelike hump on the southwest flank of the cone. After a few days of cineritic activity an inner or "daughter" cone, called the Ombligo (navel) by the natives, showed itself above the crater rim, eventually rising to an elevation of about 30 meters above the old crater edge. This inner cone continued to grow and finally merged with the main cone, the last perceptible trace of which was a narrow bench that marked the old crater rim (pl. 22*A*).

From April 20 to June 8 the eruptive activity, while continuing to throw out great quantities of bombs and ash, took place with comparatively little noise, usually a recurrent roll like heavy surf upon a rocky coast, with occasional deep thunderous explosions. Although more variable, the crater continued in full activity, with a heavily ash-charged column rising in volutes to a great height, showering bombs on the cone and its vicinity and ash over a wide area of fields and forest. It became necessary for the villagers of San Juan Parangaricutiro to clean the roofs of their houses every 2 or 3 days to prevent collapse.

It was during this period, too, that strong winds sometimes raised a dense dust that obscured the sun, which together with the heavy ash-fall made it necessary to use lamps in San Juan Parangaricutiro during the daytime; and in Uruapan, 25 kilometers to the east, street lights were turned on, and motorcars found it necessary to proceed with headlights aglow.

In early June heavy wet ash fell that bent and broke large branches on the trees as far as 5 kilometers to the north. The noise of breaking trees and branches was described as resembling gunfire during a skirmish in war. Many young pine trees not broken were bent double to form arches of ash.

RECURRING FLOWS

In early June Parícutin entered into a new and violent phase of activity characterized by intermittent but very violent explosive activity from the crater, by various lava flows, and by the rafting of the north side of the cone on three occasions. From early June into August the volcano showed its most varied and spectacular activity. The variety is described from notes taken during our stay from June 9 to 19.

June 9.—At Uruapan this day began beautifully and clearly after the deluge of rain of the night before that cleared the atmosphere of volcanic dust. The "smoke" plume of Parícutin was sharply visible from Uruapan, rising several miles vertically, with a long dark curtain of ash carried to the south by the winds. At 9 a. m. clouds began to gather in all directions, as is usual in this region at this time of the year, but especially about and below the long dust curtain. Compared with the white vapor clouds, the appearance of the eruptive column was pinkish brown.

Upon approaching San Juan Parangaricutiro at 2 p. m., we could see through a gap in the encircling hills the cone of Parícutin and its huge billowing column of ash. At 3 p. m., while we were awaiting our horses and mules, a casual glance toward the volcano showed a remarkable change, a rather sudden and marked decrease of the smoke to a thin languid column that shrunk perceptibly as we watched, as if a valve had been closed and the volcano was subsiding to rest. A half hour later there remained but a thin wisp of pale vapor and an occasional quiet burst of large bombs with little ash; and an unnatural calm settled over the cone. The change was so unexpected and so unusual that we all thought the volcano was dying and many of us gathered with the Presidente Municipal for a celebration.

We arrived at the camp on Cerro de Jarátiro about 4 p. m. The Quitzocho flow was now completely covered with ash, except for the peaks and crags that projected above the surface or faced the edge of the flow, and the numerous fumaroles along the lava front lazily gave off their usual white or bluish fumes.

The bursts from the crater threw out a scattering of large viscous bombs, without ash or much visible vapors, accompanied by a deep throaty grumble. This rather tranquil state did not last long. Soon the activity began to increase, gradually, almost imperceptibly, until at 9 p. m. the bursts followed each other in rapid succession. Strong explosive bursts now came each ½–4 seconds, hurling large blocks, some to a height of more than 600 meters (12 seconds to fall). These bombs showed many irregular and changing shapes; rods, clubs, and macelike projectiles, some like boomerangs or T's and a surprising number like birds soaring through the air, all indicative of the viscous state of the bombs. Upon falling on the slopes of the cone, these bombs broke into cascading fragments or rolled down the slope like pinwheels, casting incandescent fragments in leaping arcs before them. The noise of the large explosions was tremendous, and one could feel the blast of air at the camp 1½ kilometers away. Occasional overwhelming explosions gave advance notice by a vivid pink suffusion of the rising column, followed by a striking arc of yellow light (flashing arcs) that shot up into the sky from the crater. These were followed by bursts of huge irregular masses of lava, incandescent orange, which, upon falling on the slopes of the cone, made fantastic cascades of glowing rock. Six seconds after the explosion the sound wave reached us, an overpowering roar, reverberating around the hills like the roll of thunder.

At midnight there was a vivid electrical storm south of the region in the area of heavy dust fall. Early in the evening I noticed a slight offset in the summit line of the cone, as if a segment had slumped slightly. By midnight this straight displacement had become a distinct sag (fig. 112).

June 10.—The indescribable noise and confusion continued until 2 a. m. At 2:10 the tremendous roar suddenly ceased. At 2:11 a. m. there was one last tremendous blast; then quiet. I [Foshag] went to the door of the cabin but could see nothing more than a large dust cloud. When this began to clear, I could perceive an occasional incandescent bomb rolling down the indistinctly visible cone. When the dust had sufficiently cleared after this last explosion, the crest of

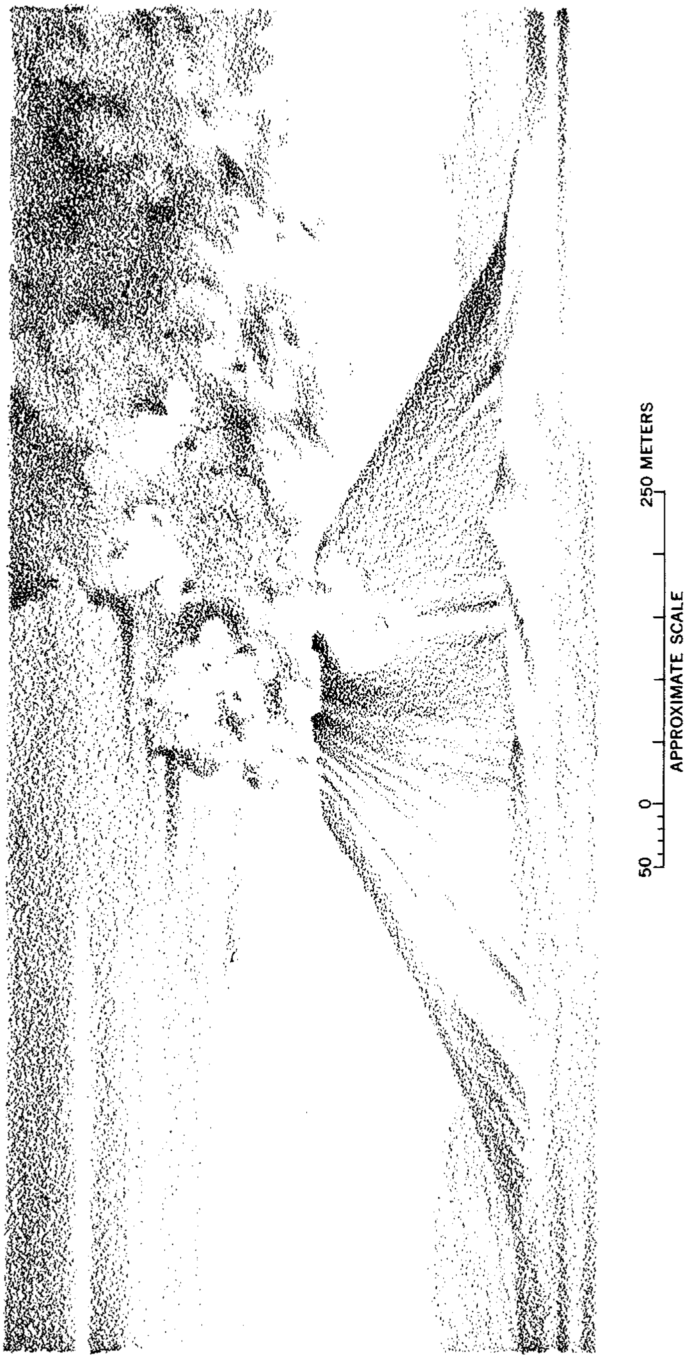


FIGURE 112.—Parícutin volcano on June 9, 1943, at 9 p. m., showing the cone, complete except for a slight slump in the north crater rim. Ash-covered Quitzocho flow in the foreground.

the cone was no longer straight but saddle shaped, but it remained for morning to reveal what had taken place.

Soon after, the crater resumed its activity, now without perceptible noise but with a beautiful column of rising incandescent bombs, one burst following another in rapid succession; and thus it continued until daybreak.

Daylight revealed a huge break in the cone (fig. 113). A segment embracing about one-quarter of its perimeter had moved out (carried out by lava we learned later). The side walls of the break were steep, and the slumped portion lay in two long terraces at the base of the cone. The volcano was now very quiet, with only rare bursts of bombs but with a heavy, slowly rising eruptive column.

The summit of the lower of the two main terraces sloped down from the east end of the break at a 5° angle to the west end, and its front showed a regular wall with slopes at the angle of repose (about 32°). This lower terrace advanced very slowly toward the north, its movement dislocating rocks on the slope, which rolled down raising a fine pinkish dust.

The western extremity of this lower terrace had a reddish oxidized color, and the frequent falls of rock raised plumes of pinkish ash. At 11 a. m. incandescent moving lava appeared at this point. For the first time in the life of the volcano, the eruptive activity of the crater had so diminished that one could reach the base of the cone with reasonable safety, and we were able to watch the lava at close hand. The lava front, although incandescent in the crevices and gashes and in the blocks that spalled off, showed no liquid lava. It advanced at a rate of 30 meters per hour as an apparently solid wall of rock and rubble. Hugh incandescent masses were dislodged and rolled to the foot of the flow, and there was a continuous disintegration and streaming of incandescent pebblelike fragments or sand down the seamy lava front. Blocks on the lava front disintegrated with a continuous crackle, to which was added the tinkle of sliding scoria. The hottest incandescent lava was orange red. No visible fumes were given off, and there was no perceptible odor. The flow carried a cover of ash, the surface of which was wet from the rains and steamed from the heat below.

All during the day the crater was quiet with only rare explosive bursts that yielded a huge eruptive column rising silently to a height of about 5,000 meters.

At about 7:40 p. m. a thin white column of vapors suddenly appeared near the northwest base of the cone. This column was larger than the fumaroles and within the main part of the Quitzocho flow where no fumaroles were situated. Within a minute or two the base of the vapor column became suffused a deep pink, indicating a reflection from

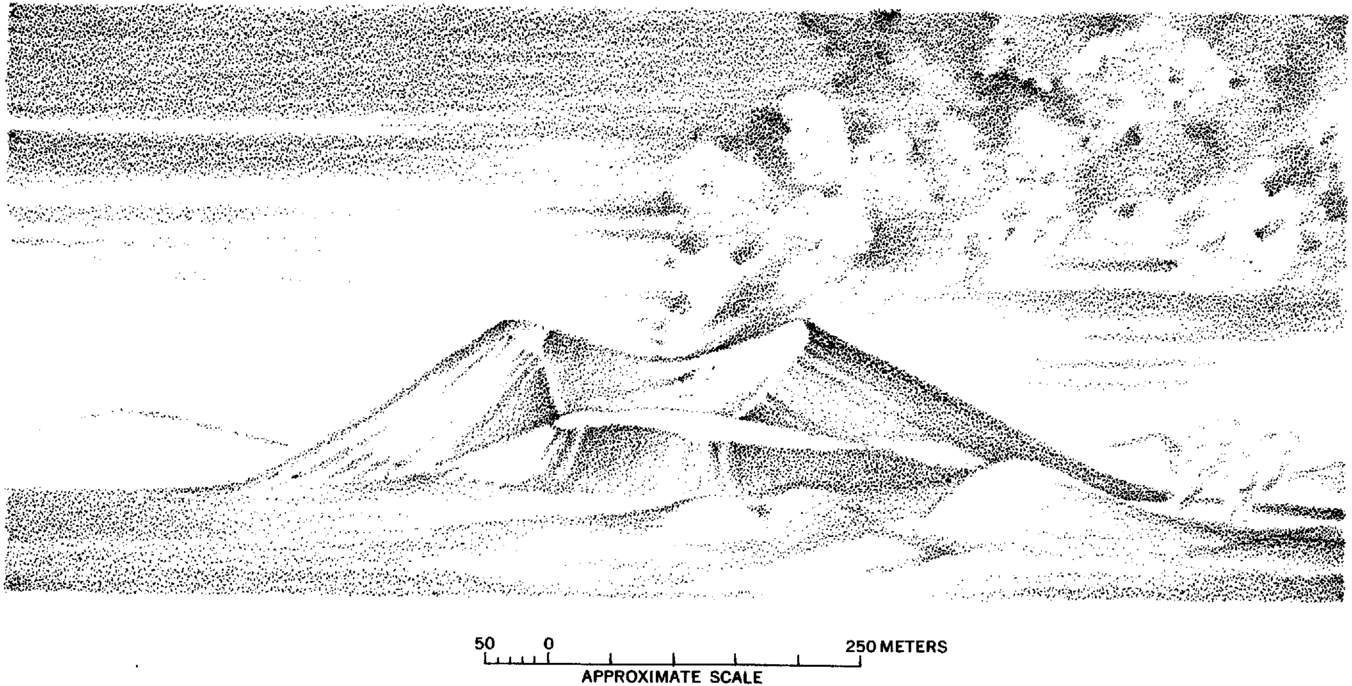


FIGURE 113.—The cone on the morning of June 10, 1943, showing slumped north side, the slumped block as a high sloping terrace, and lava flow to the right. The knoll to the right indicates the beginning of the Quitzocho ridge.

incandescent lava, which rapidly increased in intensity. We hastened to the spot, crossing over a newly formed ridge of ash, furrowed and seamed by small crevasses (pl. 29*A*). This ridge, which was later to show striking changes, we have called the Quitzocho ridge. Beyond we found a new low cliff of lava, with incandescent patches, slowly advancing and disintegrating. Huge incandescent blocks broke from the front and rolled to the foot; and small incandescent fragments, hardly distinguishable from liquid lava, streamed down its face.

About 15 minutes after our arrival, a spot on the lava front became more incandescent (orange yellow) and began to work like slowly rising dough. In one-half a minute the lava at this spot began to flow and spread, and within 5 minutes a front 5 meters across flowed down the slope like molasses. This flow, moving between the newly formed ash ridge and a knoll, upon which we had taken stance, moved so rapidly that we feared we might be cut off. From the surface of the flow small incandescent fragments of lava were sometimes blown up, with a hiss of escaping gases; or small whirlwinds formed, spiraling so rapidly as to produce a whistling.

By 10 p. m. the flow had spread over a large area, with a front 100 meters or more across. By now its advance had slowed greatly, and its surface was already black, except for the numerous cracks that furrowed it, when a second surge came, overriding the first and emitting copious white fumes tinted pink or yellow by reflection from the glowing lava.

During this activity of the lava, the crater gave off a billowing black eruptive column but with few explosions, much as it had done during the entire day. Through the night, however, activity in the crater increased, with spasmodic strong explosions.

Upon returning toward our camp we found the newly formed ridge of ash higher and more deeply furrowed. With considerable trepidation we climbed an eminence and saw at our feet the apparent source of the lava, an incandescent stream, perhaps 20 meters wide, moving noiselessly along, dappled with moving blocks of congealed black lava. Its apparent source was the foot of the collapsed terrace, from which it appeared to flow quietly and without disturbance.

June 11.—The morning was fairly clear, but clouds formed early with rain at noon. An eruptive column of billowing black ash decreased in volume until at 2 p. m. it showed little ash, sometimes none; and the opposite side of the crater could be seen through the newly formed gap in the north wall. The accompanying noise was an almost continuous growl. Fairly large blocks were hurled up, but none rose higher than the old crater rim.

In midafternoon there were two blasts from the crater about a second apart. One from the center of the crater ejected incandescent bombs, the second, near the west rim, dense black ash (the first indication we have had that the crater sometimes had more than one vent).

Activity from the crater slowly increased during the afternoon. The flow of last night had practically ceased, and only a few short segments of the front showed slight advance. The flow extended from the west foot of the lower terrace, passed between the foot of the cone and the newly formed ridge, and covered a wide area between the cone and Cerro de Canicjuata.

June 12.—The morning was heavily overcast, and rain drizzled down. From a station northeast of the cone, two eruptive columns were distinguishable—the one from the western part of the crater gave off dense gray smoke; the second, near the northeast rim, yielded some bombs and less ash.

At 2:30 p. m. the rain ceased somewhat; and when we went out to place some collecting tubes in the fumaroles, we found the new ridge now increased to about 30 meters in height and, beyond the ridge, new lava flowing down Parícutin Arroyo in the direction of Parícutin village. This already well-advanced lava flow had its apparent source beneath the ash near the vent of yesterday's flow. As the flow moved across ash-covered fields to the edge of Parícutin Arroyo, its front became steeper until it was entirely free of the congealed clinkers with which most flows are covered, exposing the actual moving incandescent lava below. Its advance took place as slowly bulging lobes, which gave the entire moving front a gross botryoidal surface, bulging and cracking with an everchanging surface. Such clinkers as formed rolled down this front to the arroyo below. As the bulges reached a certain degree of protuberance, they tore off and rolled down the arroyo slope as viscous masses. Most prominent was a basal bulge, slowly turning under and incorporating within itself the accumulated clinkers at the base of the flow. Sparse bluish fumes arose from the lava, but the only sound was the tinkle of moving clinkers. The advancing front was 4–5 meters high. This flow we have called the Parícutin flow.

During the afternoon, activity from the crater subsided until there was little smoke from the cone. One could now clearly discern a large crater to the north, separated by a high, steep medial septum from another to the south. The north crater was entirely inactive, but the south vent was in active eruption. During the night, this south vent yielded a fine pyrotechnical display, hurling incandescent bombs 1,000 meters into the air with frequent bursts of black ash. This eruption was noiseless except for the swish of the bombs through the air and their dull thud upon the slopes of the cone.

Throughout the night we noticed new glowing spots in the old ash-covered Quitzocho lava, which proved to be not new cracks but the rejuvenation of older fissures.

June 13.—The day was cloudy and rainy when we awoke at daybreak to a tremendous grating roar that continued without interruption, except for very rare periods of one-half minute of complete silence. At our camp 1½ kilometers away the vibrations from this roar were perceptible and sometimes were even strong. From the south crater a small column of smoke and small bombs shot up in a swift and continuous stream, a veritable geyser of fire, but the north vent was inactive.

Don Felipe Cuara came on horseback in some agitation to tell us that Parícutin village was threatened by lava (the Parícutin flow). On arriving there, we found the lava of yesterday had advanced well beyond the limits of the Mesa del Corral flow and was moving forward at a rate of 25 meters per hour but spreading laterally at only 2½ meters per hour. With Parícutin village located on a low ridge, we concluded that the lateral push of the lava would not be sufficient to cover more than perhaps a few of the lower houses. We counselled, however, the people to evacuate the town, because their fields were already beyond use from the heavy cover of ash and there seemed no surcease from the continuing ash falls. The Mexican Government had offered them facilities to evacuate their village and to settle on new lands in unaffected areas. This was sad advice to a people so deeply attached to their soil, and many were loath to accept it.

June 14.—During the morning hours a variety of noises came from the crater. Sometimes the sounds were roars, and occasionally a tremendous explosive burst, sometimes a sound like the sigh of a high wind in the pine trees. The noises came chiefly from the south vent, but there were erratic bursts from the north crater.

In the early morning a new lava flow burst out on the upper slopes of the cone above the upper terrace, between a resistant pyramidal remnant of the cone and the eastern wall of the break. Its point of origin was about 75 meters below the lower lip of the north crater, and the lava flowed as a cascade down the terraced slopes to the northeast base of the cone and beyond (fig. 114). This flow we have called the Lagunita flow, because it invaded and covered the lands of La Lagunita. The lava emitted bluish fumes, sometimes tinged a brownish yellow. The flow advanced at a rate of 15 meters per hour into the dead pine forest.

The north crater gave off faint bluish or brownish fumes; at rare intervals, bursts of incandescent bombs of black ash. The south crater emitted a continuous eruptive column accompanied by occasional roars or puffs similar to a starting locomotive.

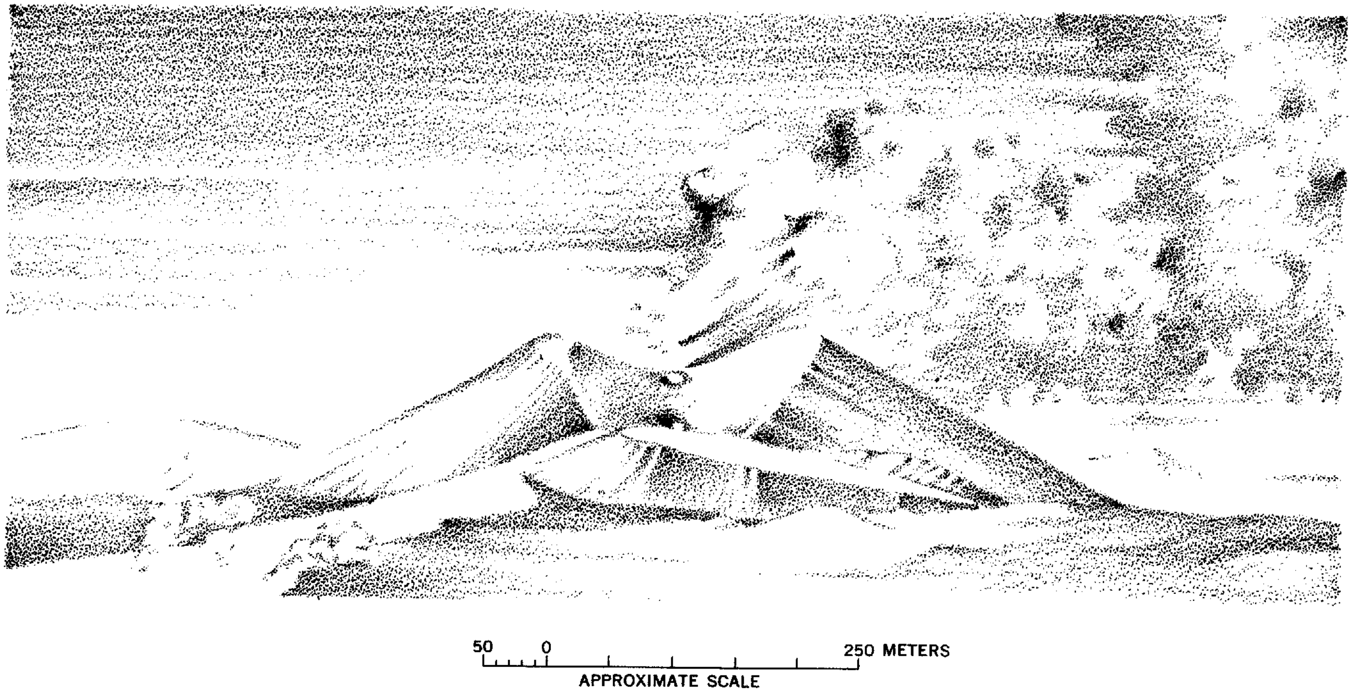


FIGURE 114.—The cone on the morning of June 14, 1943, showing the break in the north slope of the cone, with the north crater vent; below it the lava vent above the slumped block; the lava flow is toward the left and the smooth Quitzocho ridge to the right.

We went to Parícutin village at 4 p. m. and found the lava still advancing. The front progressed at a rate of 21 meters per hour, and its lateral push had carried it within 80 meters of the first house of the village. Many houses were being dismantled, and trucks had already arrived to evacuate the people.

At 6 p. m. the eruptive column rose slowly from the cone with a low sound like a beating surf. The locomotivelike puffs continued and came, perhaps, from the north vent. With darkness the incandescent cascade of the lava, flowing down the cone, produced a magnificent sight.

June 15.—In the morning we went to Parícutin village. The lava flow had slowed to a low speed, greater toward the northwest in the direction of San Juan Parangaricutiro, much less laterally. The west side of the flow was then about 20 meters from the first house in the village, and the inhabitants had placed an additional cross before the dwelling to ward off the danger of its destruction. A few weak fumaroles had already formed in the flow, indicating that it was now practically at rest; and the fumaroles were beginning to yield thin white, yellow, or orange sublimates.

In the afternoon we went to the Lagunita flow, which moved down the terraces from the upper vent. This had spread in a sheet between the Quitzocho flow and the low hills bordering the eastern edge of the valley. The Lagunita flow was thicker than the Parícutin flow and advanced more slowly, 5–10 meters per hour. It was viscous, bulging here and there as the moving lava broke through the front of advancing rubble. There was no odor, few fumes, and little noise, except for the tinkle of sliding clinkers. The flow followed the general slope of the terrain but moved over low slopes of hummocky ground and low knolls.

At night the volcano offered a magnificent sight—a bright incandescent eruptive column showered bombs upon the cone, and the two brilliant rivers of orange lava cascaded from the vent to the base of the cone and flowed to the lava field in the valley, where myriad lights looked like a city viewed from a distant hill.

At 9:30 p. m. the lava vent began to spurt with a noise like a starting locomotive. Fountains of lava, estimated at 5 meters high, appeared at the vent, hurling viscous masses to a height of 50 meters. With this increased activity in the lava vent, the north crater resumed weak activity, throwing out small bombs and glowing ash with quantities of black smoke or thin wisps of vapor. The north crater rapidly filled with ejectamenta from the south vent. Most of the bombs fell to the west, and the western part of the break in the cone was rapidly being repaired, while the east wall of the break was still much in its original condition.

June 16.—In the early morning the north vent threw out much ash and a heavy fall of bombs, and the south crater was steadily active, continuing so until 11 a. m. when the north crater ceased its activity and then showed little action during the remainder of the day. The east flow continued its slow advance. Its front was 5 meters high. The lava seemed to show less incandescence, and the flow appeared to be subsiding.

June 17.—The day was clear, and white fleecy clouds were scattered in the sky. The north crater was now filled by ejectamenta from the south vent. The day began with heavy explosions from the south vent, hurling out huge bombs but little ash. To the west of the main eruptive column, a plume of vapors lazily rose as if it came from a second vent in the south crater. At 7:45 a. m. the heavy explosions ceased, and for 2½ hours there was a quitely rising eruptive column with intermittent blasts hurling up large irregular masses of lava.

At 10:20 a. m. sudden jets of lava appeared near what had been the summit of the pyramidal block and 25 meters above the earlier lava vent, which had ceased flowing (fig. 115). This new lava moved rapidly, like a red tongue, down the 40° slope and dropped about 100 meters to the level of the upper terrace. A second surge of lava almost immediately followed the first. Twenty minutes later a tremendous explosion from the new vent hurled huge molten masses of lava into a fan-shaped burst, and the wall above the new vent began to crumple slowly and slump, exposing a red glow, apparently of incandescent ash and rock. It appeared that the gradual attrition of the continual explosive bursts had exposed the interior of the cone very close to the conduit of the north vent. The flow of lava rapidly increased and 25 minutes after its first outbreak was 10 meters wide and advanced rapidly down the steep slope.

During this lava activity the south vent emitted a heavy eruptive column, rising silently or with a low sound like surf. Now, however, the south vent and the newly formed throat entered into a spasmodic but strong series of explosions, with violent blasts from 15 minutes to an hour apart, both vents hurling out huge masses of viscous lava. Sometime during this period of violent explosive activity, the lava surge ceased rising in the conduit, and the flow abated. At 2:04 p. m. another new vent broke forth, without noise, near the locus of the first. Soon after, the lower lip of the north crater began to show some incandescence, as if liquid lava was oozing through the wall, which was immediately followed by a tremendous cascade of incandescent lava flowing down the west side of the break. This surge of lava lasted only 3 minutes but was followed 5 minutes later by a lesser and slower surge that appeared to be more viscous, tearing into huge blocks which rolled down the steep slope as it advanced. This was in turn followed

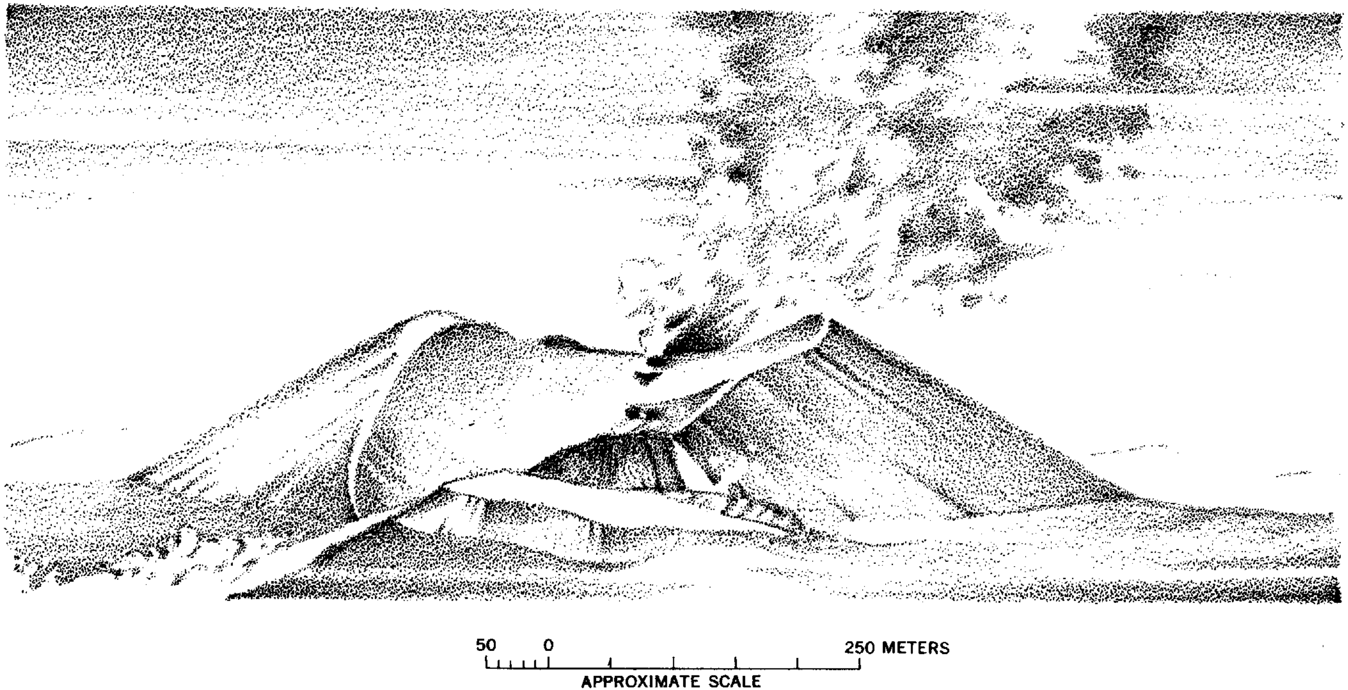


FIGURE. 115.—June 17, 10:20 a. m. South crater in eruption behind the crater ridge, the north vent in eruption near the top of the break, an eruptive vent immediately below, a lava vent below it, a lava cascade from the edge of the break toward the right, and a lava flow between the cone and the slumped block to the left. Between the lava cascade and the lava vent a resistant block.

by a tremendous surge, which rolled slowly over and over. During the period of lava surges, the east flow appeared dormant and the south crater much reduced in activity.

The cone showed a cirquelike wall behind the Lagunita vent. The wall behind the new vent changed to a similar cirque, about 50 meters high, at the summit of which began to appear, through attrition, a low black cliff, with incandescent spots and occasional streamlets of either liquid lava or incandescent fragments. This cliff was obviously more compact than the loose ash and bombs of the cone and was perhaps the inner welded surface of the old north crater.

At 4:49 p. m. a new surge of lava from the new vent was accompanied by a heavy explosive burst.

At 6:27 p. m., blowing like a bessemer converter, the old north crater reopened immediately above the incandescent cliff as a vent about 3 meters across with the continuous emission of smoke and the streaming of incandescent bombs. At the same time, the lava flow increased, and the whole front of the advancing tongue tore off and rolled down the steep slope like a huge red snowball. The lava now flowed continuously with greatly augmenting surges at about hourly intervals. With each increased surge tremendous masses of viscous lava tore from the advancing stream and rolled down the slope. During this lava activity, the action of the south crater was slow and steady with a continuous sound like beating surf. Explosive activity from the north crater consisted of a rare heavy burst with much black ash and "flames" streaming incandescent ash.

June 18.—In the early morning hours explosions occurred in both the north and south vents simultaneously at regular intervals, suggesting that the two crater vents were connected. Lava flowed in a broad stream down the slope of the upper terrace and in a broad cascade over the lower terrace and spread in a broad sheet over Llano de Quitzocho and La Lagunita. The lava was not the rough and hummocky flow of the Quitzocho lava but a broad flat sheet, very gently convex in cross section and covered with a characteristic blanket of clinkers. Unlike the Quitzocho flow it had only a few weak fumaroles.

During the morning the south crater gave off a continuous heavy billowing column, while the lower lava vent gave off occasional bursts of black ash, at times with great violence (fig. 116). The lava flowed intermittently, with occasional surges. At 12:25 p. m. a huge lava front advanced slowly toward the east from a point below the lava vent, spreading out to a front about 50 meters wide and then advancing more rapidly, throwing out several lobes down the steep slope of the upper terrace. In the 15 minutes it took to reach the base of the cone, the lobes had already congealed and remained motionless on the

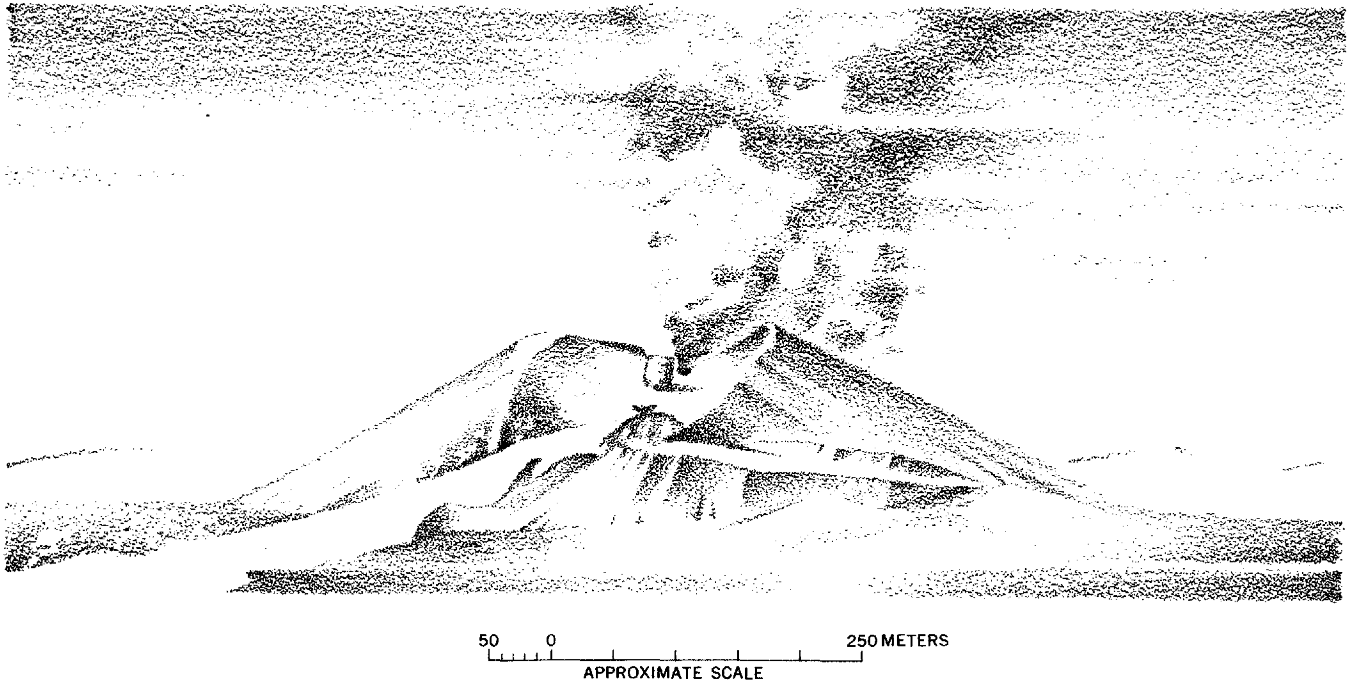


FIGURE 116.—June 18, 1943, 11:20 a. m. Eruption from south vent; eruption from north vent in upper part of break, resistant ridge on crater rim and resistant plug in the break. Below the resistant plug the lava vent, and the lava flow toward the left.

steep slope of the terrace, an indication of how rapidly a flow can completely congeal, even on very steep slopes.

At 12:50 p. m. activity in the south crater and the lava vent spasmodically increased in intensity. The south-crater activity increased noiselessly.

During the morning, a resistant plug remained prominently defined against the smooth ash walls of the concave break. At 11:20 a. m. two earlike protuberances gave it the appearance of an owl, but by noon it had already begun to gradually disintegrate. At the time of the heavy eruption of late morning and early afternoon, it slowly diminished in size. At 12:28 p. m. a new vent appeared where the plug had been, its orifice perhaps 10–15 meters across, with what appeared to be an incandescent rim or aureole. This vent was about 10 meters above the previous one, which was in violent eruption only a few minutes before. From this new vent eruptive material rushed with tremendous velocity, like a huge blow torch, roaring continually with a harsh grating, reverberating roar.

The activity of the volcano had now reached a tremendous intensity. The south crater threw out great masses of rock and a heavy column of ash, and there was spasmodic heavy activity from the lava vent. One could feel the percussions of the eruptive blasts at the camp, and the ground was in frequent trepidation. Surges of lava flowed from the vent. The north wall of the south crater became fissured and began to show distinct attrition and lowering of its rim.

June 19.—The north slope was now a smooth concave swale, with lava flowing from a moundlike vent about two-thirds up the cone and rising some 10–15 meters above the upper terrace level. From this vent thin blue vapors arose. Some 15 meters above this was a small vent perhaps 4 meters across from which ejected material rushed as if from a blowtorch, yielding a small column of vapors and ash. The saddle-shaped crater rim, with a black resistant comb, formed a low scarp to the east. The lava flowed quietly down the terrace toward the east and spread over the lands of La Lagunita (pl. 24*A*).

This period beginning on June 9 and continuing for about 1 month was one of the most active and violent in the life of the volcano, surpassed only by the tremendous eruptions in late July. The striking changes that took place in the configuration of the broken cone, the kaleidoscopic variations in the eruptive activity, the rapid shifting of the lava vents, and the tremendous surges of viscous lava set this period apart from any other period in the history of the volcano. The alignment of the shifting lava vents in a northeasterly direction suggests a lava source from a fissure striking in this direction. The nature of the apparently solid but incandescent "combs" and "plugs"

338669 O—55——5

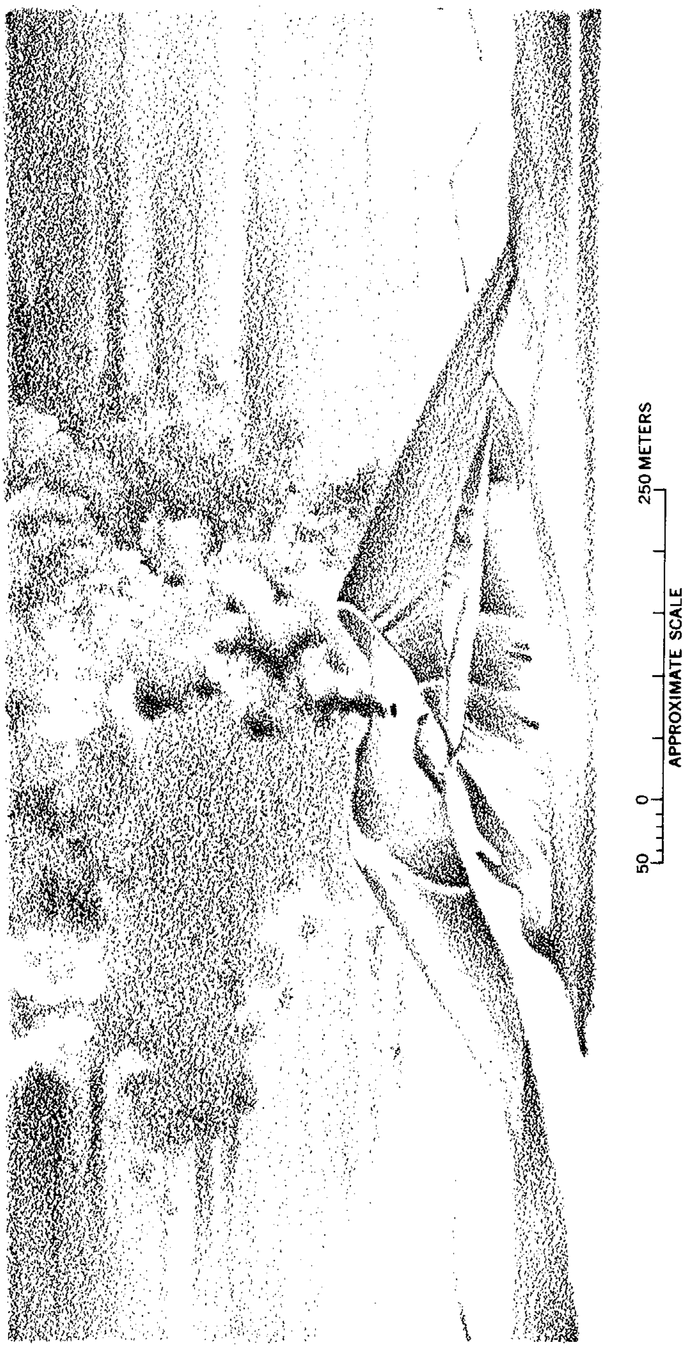


FIGURE 117.—Disappearance of the resistant plug on June 19, 1943, by disintegration by a vent at its base. Below this vent is the resistant dome, from the base of which issues the lava flow.

unfortunately could not be determined. The significant changes in the configuration of the cone are shown in figures 112 to 117.

QUITZOCHO RIDGE

One of the conspicuous features of the volcano, until covered by the lavas of 1947, was the high ridge that extended from the northwest base of the cone to Cerro de Jarátiro. This ridge had its inception during the night of June 10, at the time of the break in the north side of the cone. Just how the ridge began cannot exactly be told, for during the day our attention was attracted by the phenomena of the advancing terraces and the outbreak of lava. At 7:40 p. m. our attention was drawn to the northwest base of the cone by a rising column of vapors. Upon hastening to the area, we found a newly formed ridge of furrowed ash. At one point a large tongue of torn and twisted lava projected through the disturbed ash cover. Dr. Frederick H. Pough, who was at the spot somewhat earlier, has described the area for us as follows:

Toward evening I noted an ascending column of steam about 275 meters west of the slowing flow of this morning. As it got darker a glow began to show at its base, like coals shining on steam. Upon closer approach it seemed to be coming from the top of the other side of a pressure ridge composed of loose, sliding pumiceous fragments. Thinking that a new lava flow must be coming from the other side of the ridge, I went around the nose and found a second ridge identical in appearance and character. It was then apparent that hot lava must be exposed near the top of the ridges.

The ridges were about 9 meters high and a little difficult to climb because of the loosely furrowed ash of which they were composed. They were also a little warm to the touch. As I surmounted the top I saw below a bed of small hot rocks about 30 meters across spread out before me. The margins were of larger rocks, covered with the loose material on which I was standing. As I knelt to set up the tripod of my camera I felt a number of shocks as if the ridge were moving. I did not stay long, only long enough to take a few pictures. The top of the ridge was about 1½ meters above the level of the hot rocks. The surface was dark, the inner cracks were red, in fact it had the appearance, on a giant scale, of a furnace bed, pretty well burned down.

Shortly after descending the slope, the western ridge crumpled away as the lava bed rose a little higher and began to advance rapidly, ferrying along on its surface the more solid stones. The front advanced to the northwest, covering about a quarter of a mile in about half an hour. The whole front was actively crumbling away, and the flow advanced in a fairly thin sheet not much over 2 or 2½ meters high at the front. A tremendous whirlwind rose above the flow at the site of the former ridge; at the time it was thought to be escaping gas, but it later was decided to be a little tornado caused by the heat.

At about this time I was joined by Foshag and Cooper and we ventured up on the eastern pressure ridge to a point above the source of the lava. Little movement was apparent in the bed even now, though the slope underfoot was shaken by movements. The ash beds bordering the glowing lava were clearly being raised. They kept crumbling at the margins, and little trickles of incandescent dust ran down onto the furnace bed. The heat was intense and the site on which we were standing was moving; since we thought it might collapse into the lava, we did not remain there long.

This original ridge formed a line of low hummocks extending from the base of the volcano to the edge of the Mesa del Corral flow at the foot of Cerro de Jarátiro (pl. 29*A*). By June 12 this ridge was about 10 meters above the old ash-covered surface of the Mesa del Corral flow, and the ash showed much evidence of oxidation by intruded lava. On this day, too, a new flow of lava, the Parícutin flow, issued from the south end of the ridge near the base of the cone and flowed toward the north over the old ash-covered lavas.

The ridge grew almost imperceptibly, or at least we paid little attention to it, for at first it was little different from the usual hummocky aspect of the heavily ash-covered Quitzocho and Mesa del Corral flows, and the numerous outbreaks of lava from the cone attracted our attention. The smooth ash cover was elevated and domed, broken by numerous cracks, with patches of pushed or slumped ash (figs. 118, 119). The top of the ridge showed deep fissures in the ash and displaced or raised blocks of ash. A few patches of reddish oxidized lava were exposed in the flanks of the ridge. The ash was obviously being slowly raised into a domed ridge by the injection of lava beneath, perhaps by additions of fluid lava to the underlying old lava flow from a source at the northwest edge of the lower terrace.

ACTIVITY OF JULY

On July 17 Donald White found an apparently fresh slide of the cone on the southwest slope, directly opposite the old break on the northeast side.[14] He reports seeing clouds of dust rising from this area earlier on the same day. The glow of incandescent material was visible in the break, but no lava was observed. Steam and vapors arose from the landslide area suggesting the possibility of lava flowing beneath the rubble. This slide took place at the locus of the earlier Mesa del Corral vent. Later flows were to break out in this same sector.

The Lagunita lava (pl. 25*A*) on the northeast side flowed intermittently until July 19, when its movement down the slope was very slow, about 1 meter in 5 minutes. In the evening of the 19th the last weak surge of lava from its vent was observed. The break in the northeast slope of the cone was now reduced to a wedge-shaped segment that formed a sag in the upper line of the crater. At the inverted apex of the triangular break about half way up the slope of the cone was the lava vent. The lava flowed down two trenchlike channels, spreading over the fields of La Lagunita and Turímbiro. This flow was similar to other flows, a blocky lava, its surface covered by a mantle of blocks and clinkers. The last lava of this flow moved as a tongue over the

[14] Unpublished notes.

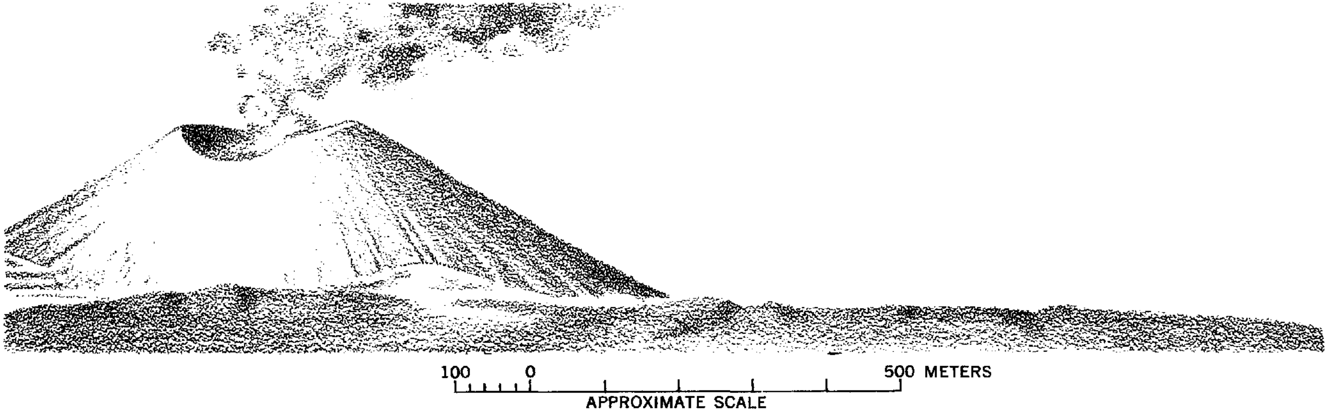


Figure 118.—Quitzocho ridge in early June, showing the smooth ash-covered Quitzocho and Mesa del Corral lava flows.

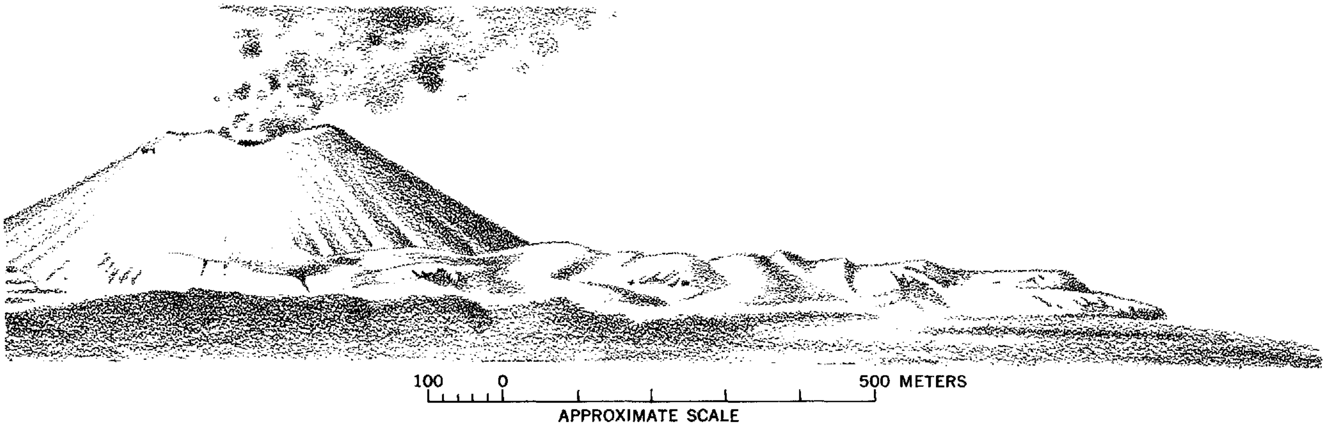


Figure 119.—Quitzocho ridge after the flow of June 9, 1943, showing the smooth ash raised by injection of lava below.

ash-covered Quitzocho lava between the eastern end of Cerro de Jarátiro and the base of the cone.

With the diminution of the lava flow from the vents, the break in the cone began to fill with ejectamenta from the crater. With each new surge of lava, now at intervals of 2 days or more and then of short duration, ash slides occurred in the break; but with the total cessation of lava flows, the cone very soon returned to its normal even slope.

The last phase of this interesting period of lava flows was the brief outburst of chimneylike vents on the slopes of the cone (pl. 26*A*), these vents coinciding as nearly as can be determined with the lava vents of this period.[15]

On July 27 we returned to Parícutin after a day's visit to Uruapan and found striking changes taking place. In traveling from Uruapan to San Juan Parangaricutiro, we were struck with the large quantity of pinkish or reddish dust that arose from somewhere near the north base of the cone. This dust obscured the cone, so that we could not clearly perceive its state, although it was apparent that some significant change was taking place.

From San Juan Parangaricutiro we passed through the now entirely depopulated village of Parícutin, where many of the houses had collapsed from the weight of ash. The Parícutin lava flow that threatened to engulf the village had now practically ceased its advance, although an occasional creaking noise indicated that there remained some slight movement in the mass. Scattered weak fumaroles had formed, spotting the lava with thin patches of white and yellow salts.

Seen from the Parícutin Arroyo, now completely filled with lava, it was strikingly evident that the Quitzocho ridge had greatly increased in size and that the north slope of the cone had suffered another slump such as we had observed in June. According to our informants, this new break in the cone and the changes in the topography of the Quitzocho took place at 2 p. m., during our absence, without preliminary warning (pl. 24*B*).

The cone showed a wide concave break on its north front, now partly restored by the fall of bombs and ash. The north side was a rather flat facet of the cone, at the foot of which was a rubble terrace, or rather a ridge, for a shallow valley separated the terrace from the cone. This terrace, oriented towards the north, joined the Quitzocho ridge to the cone. Between the terrace and Quitzocho ridge was a saddle, which we frequently traversed later in going to and from the opposite side of the cone. The south end of the Quitzocho ridge rose about 130 meters above the original surface and was crowned by several large irregular masses of rock. These rock masses, we were

[15] Unpublished notes of Ezequiel Ordóñez.

later to discover, were congealed lava and the remnants of the lava vent from which the June lavas issued. They had moved several hundred meters toward the north, carried out upon the surface of a lava flowing below. For many months the incandescent fissures in these rocks served us as guides at night, and the rocks we called Los Faroles.

The Quitzocho ridge had changed from a relatively low ridge (pl. 29*A*), with smooth slopes of velvety-appearing ash to a mesa capped by bedded ash (pl. 30*A*) and with steep slopes of pinkish and reddish oxidized ash and rubble. As the sides slowly expanded, blocks of lava and streams of clinkers rolled down the slope, raising a pinkish or reddish dust that settled over the wet, black ash that covered the old Quitzocho and Mesa del Corral lava flows.

But the most striking change was shown by the ridge front, facing the slopes of Cerro de Jarátiro. This front, now about 100 meters high, was a steep, rugged and broken scarp, turreted with huge masses of lava. This scarp was ever changing its features. The huge exposures of congealed lava were in a constant state of disintegration to small rubble or fine sand which streamed down the seamed face of the ridge like small flows (fig. 120; pl. 29*B*). A viscous lava frequently bulged from beneath the huge blocks; and the whole front, although apparently congealed, was slowly advancing. At times huge blocks of rock many meters across slowly tilted forward, then rolled to the foot of the face with an earth-shaking thud. Although many masses were lost from the front by disintegration or fall, new ones formed by crevassing of the front. One of the results of this action was an accumulation of debris at the foot of the slope made up of angular fragments ranging from 5 meters in diameter to fine sand and dust. During this disintegration pink dust rose in copious quantities. At night we observed what appeared to be short tongues of flame playing over some of the crevices in the congealed masses.

Within the next few days several flows broke out laterally, like pigs from a sow, from the Quitzocho ridge. Very near the north scarp of the ridge nearly a kilometer from the cone, the first, a short flow, issued from an orifice on the west slope and encircled the nose of the ridge. A second broke out from a point near the first and flowed a short distance toward the northwest, yielding a scarp of jumbled blocks and clinkers (pl. 42*B*). A third flow breached the ridge about 100 meters back from its nose and poured out in a brilliant flood of incandescent lava, carrying with it huge blocks riding majestically down the incandescent stream. This sheet flowed quietly but rapidly at its orifice, but the front soon slowed to a speed of about 40 meters per hour. This flow, moving on top of the Parícutin flow, reached about one-half the distance of the Parícutin flow and there halted,

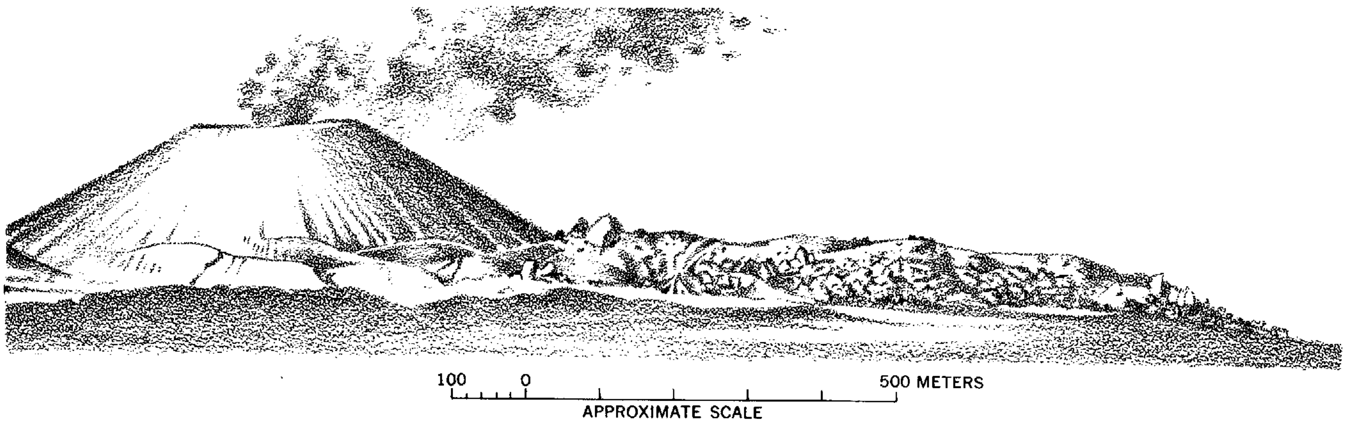


FIGURE 120.—Quitzocho ridge after the injection of lava in July–August 1943. Disintegrated lava appears from below the ash. The protuberant blocks are cores of disintegrating lava.

forming a terrace upon the older flow. This second flow toward Parícutin village we have called the Tititzu flow, because its front coincides generally with the lands of Tititzu.

Since the break of the cone on the morning of July 24, the crater was in intense activity (pls. 25*B*, 28*A*), yielding a dense and heavy eruptive column with heavy cauliflower heads. The amount of material ejected was great enough to heal the break in the cone and restore it to almost complete symmetry. Heavy ash clouds drifted to the southwest raining ash upon the pine forests of Cerros de Tancítaro. On July 31, at 11 a. m., a distinct change in the activity in the crater took place, similar to the change that preceded the break of June 10. The noise increased, and the eruptive column diminished until the activity was reduced to a thin spasmodic column of tenuous vapors (pl. 26*B*), or even to no visible vapors at all. Larger ejectamenta increased, and large viscous masses were hurled high in the air. One could frequently discern their shapes and how they changed in their flight through the air. The explosions, coming each 4 to 15 seconds apart, gave off a deep throaty reverberating roar, and the trepidations were distinctly perceptible at camp. Shortly after 6 p. m. the first remarkable "flashing arc" occurred. An arc of yellow light shot from the crater with great speed, flashed into the sky, and disappeared. This was immediately followed by a tremendous burst of immense masses of viscous incandescent lava which, upon falling on the flanks of the cone, flowed slowly down the slope. Six seconds later, the time for sound to travel from the crater to the camp, a tremendous blast of noise shook the camp. This awesome and startling spectacle brought involuntary bursts of applause from the tourists gathered near the camp, as if the spectacle were a part of a great theatrical production.

Other similar bursts took place during the night at intervals of 15 minutes to an hour. With darkness the explosions were even more awesome than in the dusk of twilight. Tongues of lava repeatedly rose high above the crater rim, there to burst into shreds (pl. 27*A*). We estimate some to have risen 100 meters above the rim. They appeared like huge bubbles, botryoidal on the surface and presumably filled with gases. When they burst, huge glowing masses of viscous lava were flung over the cone, some so far as to clear the slopes and fall on the surrounding ash field. Sometimes a second tongue, overtaking an earlier one, would tear it into huge shreds.

The heaviest explosions, however, took place within the crater, and it was with these that the flashing arcs occurred. The first signal of an approaching arc was a bright and widespread suffusion of deep pink above the crater, a reflection of the incandescent lava in the crater upon the rising vapors and the low hanging clouds above. This was followed immediately by the rapidly expanding arc of yellow light, seemingly rising with lightning speed into the sky. Quickly thereafter came the burst of huge incandescent orange lava masses (pl. 27*B*) and a blast of warm air distinctly perceptible 1½ kilometers away. Lastly came the deafening roar of the explosion.

In the morning when we visited the base of the cone, we found huge bombs scattered about. Many were spindle bombs, some 1½ meters in diameter and somewhat more in length. Large masses of congealed lava were plastered upon the other bombs at the base. All the bombs were forms characteristic of molten but rather viscous lava. One huge fish-shaped bomb measuring 7 meters long fell several hundred meters from the foot of the cone. This was the only time that we observed characteristic spindle bombs among the ejecta of the volcano.

The character of the activity and the nature of the bombs led us to believe that a lake of lava had arisen in the crater and that huge bubbles of gas rising through the conduit had brought on the terrifying explosions of the night before.

ACTIVITY IN AUGUST

During the morning of August 2, heavy explosive activity continued with the ejection of large bombs but modest eruptive columns. In late morning, explosive activity increased and at 12:30 p. m. had reached such a violence that we looked for some new event to occur. At 1 p. m. the north slope collapsed with startling noiseless suddenness. A great section, about one-quarter of the periphery of the cone, slid out amidst a tremendous confusion of ash (pl. 28*B*). Soon great jets of dense black ash shot up from the edges of the break: first on the east about two-thirds of the way up the break, then several lower down, and then from the west side of the break—each persisted for several minutes and then died down, only for new ones to break out some other place. A huge ash jet, ascending to a great height, arose from the middle of the break. The sudden apparition of these startling ash jets and the kaleidoscopic confusion of dust and fog made it impossible to obtain a clear sequence of the events that were taking place in the break. After an indeterminate period during which we watched this startling play of forces, the action subsided; and we could discern a sheet of lava moving down the slope from a vent not distinguishable to us, flowing down a valley formed by the terrace of the collapsed cone segment and the broken slope of the cone.

The Quitzocho ridge now took on new movement. By sighting from a point at the camp to a landmark on the slopes of Cerros de Tancítaro opposite, one could follow the perceptible movement of the rocks (Los Faroles) that crowned the ridge. It was estimated from rough angular measurements that the ridge moved northward almost 150 meters during 24 hours. After this first day's advance, the movement ceased but resumed several days later for an additional advance of about 75 to 100 meters.

Following the break of the cone, the crater again assumed its more normal state, with heavy billowing eruptive column; and the summit of the break underwent a period of attrition, in which a north and south crater vent again became evident, as in June. And, as in June, the south crater vent showed a more sustained and regular action than the north vent. The north vent was spasmodic in its activity, frequently quiet, sometimes yielding bursts of tremendous violence and magnitude. A feature separating the north from the south crater was a dikelike comb, extending across the saddle between the two vents. This showed many incandescent fissures at night and frequently showed areas of disintegrating blocks, but it never entirely disappeared until covered by the ejectamenta that finally healed the break.

The lava flow from the break moved toward the northwest and spread out in a broad sheet at the foot of Cerro de Canicjuata, eventually meeting the old lavas of the first Parícutin flow.

Following the events of late July and early August, the volcano settled into a state of irregular activity, the eruptive column varying from a lazy emission of pure-white vapors to dense, heavily ash-charged columns, from periods of almost silent eruptions to heavy roars, and from a few ejected bombs to splendid night pyrotechnics. During this erratic and variable period, the summit of the cone showed frequent changes in its configuration, losing its even and level outline. This was due to the shifting explosive vents in the crater and to collapse and slides within the crater itself. During the previous 6 or 7 months any irregularity in the configuration of the cone was transitory, and the contour of the cone was rapidly restored to its normal form by the heavy falls of bombs and ash. In fact, it was surprising with what rapidity a serious break in the cone could be restored.

During this period of erratic but moderate activity, no lava flowed from any vent.

On August 25 the crater, as it had in early June and late July, showed a diminution in activity followed by intense explosive activity. At first the eruptive column was greatly reduced and even ceased at times, but heavy explosions in the crater increased in intensity during the night and the following day, reaching an intensity equaling the explosions of early August (Ordóñez, 1943), causing some alarm to the observers in the camp at Cerro de Jarátiro. During this tremendous activity some instantaneous earth shocks of medium intensity were felt, and intense rumbles were heard from the depths of the earth. Six or seven times during these days sudden explosions of unusual intensity occurred. From the camp one could see vapors of a tenuous yellow arise with each explosion from the center of the crater. At the same time, bluish fumes arose from a vent to the east. With each strong explosion a huge halo (flashing arc) shot up with extraordinary rapidity, momentarily lighting up the top of the cone and even the blue sky and the clouds. A small break in the crater showed on the northeast side, exposing a small irregular crest like that seen in late July and early August. In this period of heavy explosions, lava broke out from the southwest base of the cone, yielding a small flow that moved along the south base of the cone. Another broke out of Quitzocho ridge about 600 meters from the base of the cone, and the Quitzocho ridge (fig. 121) itself showed evidences of new movement or growth. The ridge not only increased in elevation; but huge blocks, even larger in size than those of early August, semifluid in character, rolled down the high front facing Cerro de Jarátiro, raising clouds of pinkish dust.

ACTIVITY OF SEPTEMBER–OCTOBER

From late August to September 18, the crater showed variable activity (pl. 30*B*), frequently much reduced in explosive activity, erratic and weak. The bursts came at irregular intervals of from 3 to 20 seconds, often sending up no more than a single sharp finger of ash and bombs into the air.

Since the beginning of the volcano, whirlwinds charged with volcanic dust were common on the ash-covered lava flows where the cool air from the surrounding hills, meeting the hot air arising from the lava, caused atmospheric turbulence. Sharply defined whirlwinds, often rising to great heights, added a majestic new element to the landscape. Sometimes as many as a dozen could be seen; some almost fixed in position, others moving leisurely over the lava, all rotating with considerable speed. Where they encountered trees, they had the force to tear off large limbs and hurl them into the air.

On September 18 we saw many well-formed whirlwinds of striking distinctness, which formed on the slopes of the cone. A black, heavily ash-ladened eruptive column rose lazily from the crater and drifted at a low altitude toward the west. Dust from the falling bombs was slowly drawn along the slope of the cone toward the summit where it met the ash cloud from the eruptive column drifting downward. Here they began to whirl, growing upward until they met the low overhanging dark pall of the eruptive column. Some were thick and swirled languidly; others were thin, sharply defined, and rotating rapidly. Some were estimated to be a kilometer long, extending from the slope of the cone to the pall of the eruptive

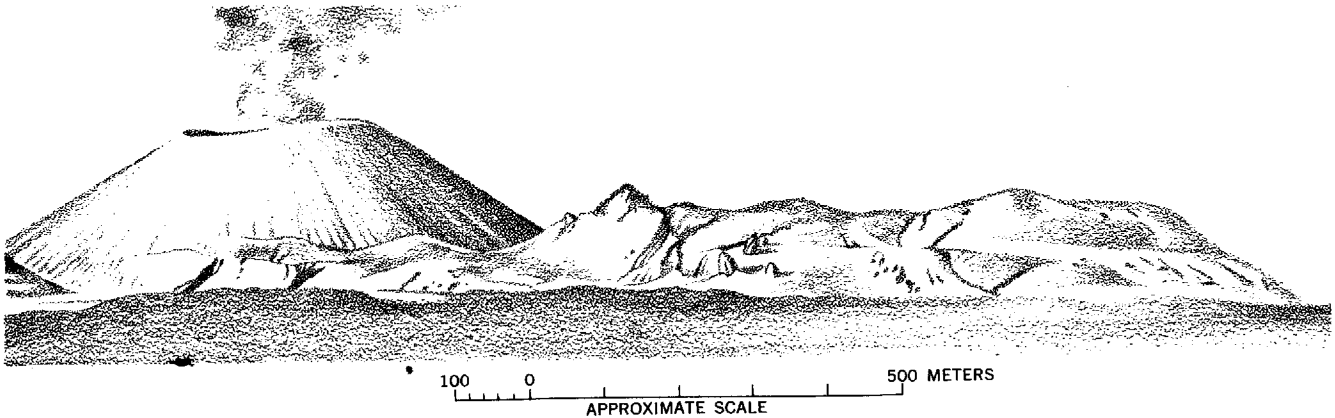


FIGURE 121.—Quitzocho ridge in late 1944. This is the final development of the ridge, with its asperities smoothed by ash.

column. Some changed their positions very slowly; others moved down the slope of the cone and across the ash fields toward Cerro de Canicjuata before breaking up.

On September 18 the eruptive column began again to subside, and heavy throaty explosions again took place indicating another probable outburst of lava which, indeed, occurred on the afternoon of this day from the southwest base of the cone. The lava advanced along the south and southeast bases of the cone, moving over the lava of August 25–26. According to Ordóñez (1943) the very fluid lava formed a low continuous fountain on the flank of the cone some 60 meters above the older lavas and flowed down the slopes between two levees. It spread out at the base of the cone as a low dome, which expanded to a flow, advancing over a width of 100 to 300 meters for a distance of 400 meters in 3 days and spreading over the basin formed by the cone and the slopes of Cerros de Tancítaro to the south.

Lava flows from the same vent were again observed on October 2–4 by Donald White, who describes them as follows: [16]

October 2, 11 a. m.—From the top of a small hill, I could see a fountain of lava rising as a pulsating but continuous column, issuing from a vent low down on the side of the cone and apparently on the eastern edge of the landslide seen in July. The fountain rises as a nearly solid column to a height of 8 to 15 meters, then falls into a lava pool and flows swiftly to the base of the cone. The vent is a point of loud noises. The fountain yields bluish-white smoke changing upward to yellow-brown fumes. The lava flow also gives off fumes of the same blue white, but less dense. This color is similar to one type of fumarole.

At 11:30 a. m. the vent is apparently moving slowly downhill by eroding the loose material of the cone. It has formed a low spatter cone about the vent except on the downhill side, which is a "river" of lava, flowing at least 1 or 2 meters per second, but increasing to 5 meters per second when a steep lip temporarily formed in the "river." The fountain died down by the time we approached it, and the lava then welled out silently, except for an occasional burst that threw molten globs as high as 45 meters into the air, with accompanying puffs of gases.

By 11:45 a. m. the gas vent has formed a trench above the outlet, this trench marking the path of downward migration of the lava vent. The trench is partly filled with spatter fragments. Steamlike white vapors that are denser than the vapors from the lava stream come from the gas vent. The vapors are emitted in puffs that do not correlate with the bursts of lava in the lava vent.

At 12 p. m. the eruptive column in the crater is much stronger, and bombs start falling outside the crater. Explosions in the lava vent die out, but the lava stream continues flowing. This lava vent is S. 35° W. of the center of the cone. There is no breakdown of the cone in connection with this flow, in contrast to former flows.

October 3, 10 a. m.—The front of the new flow is more active than yesterday morning, estimated at one place at 10 meters for 24 hours. Near the top of the main crater are peculiar radial "cracks" in the cone from which vapors escape.

At 10:30 a. m. the lava vent is still very active, the lava welling up and flowing

[16] From unpublished notes of Donald White, U. S. Geological Survey.

silently down its course; but there are "bubble bursts" with puffs of gases, and molten lava is thrown 6–15 meters in the air. A prominent spatter cone, 10 or 12 meters high, has been built up around the vent, except on the downhill side where the flowing lava keeps it open. The speed of flow is less than yesterday, and the level of the stream is lower and does not fill the trench formed by the dikes at its sides. The lava vent has kept the same position during the night, without further migration downhill. The gas vent is still active.

At 2 p. m. the crater shows what are apparently two eruptive columns: one, to the northeast, is nearly pure white like water vapor; one, to the southwest, is light to dark gray. The two columns rise constantly by pulses several seconds apart. This continued until 7 p. m.

October 4, 5 p. m.—The gas vent is still active, but the lava vent has almost ceased its activity. There are no explosions or spatter, and the lava stream, now blacker, moves much more slowly, estimated at 1 meter in 5 or 10 seconds.

October 5, 5 p. m.—No gas or vapors are coming from either the gas or lava vents, and the lava has ceased flowing from the vent. The lava level in the trench has lowered, leaving walls 6–9 meters above the lava.

On December 2 we were able to enter the trench of this flow to the locus of the vent. The actual vent itself was filled with ash, in part newly fallen and in part material that had slid into the orifice. At the vent site the ash was damp with a liquid of syrupy consistency and a strong astringent taste, and a strong odor of hydrochloric acid pervaded the spot. This wet ash was hot and steamy, indicating that gases and vapors continued to be emitted from the ash-filled vent. Downslope below the vent was a trench 5 meters wide with walls 3 meters high, the original channel of the flow. The walls showed the successive layers of repeated surges of lava. The upper layer, or flow, about half a meter thick, was without gas vesicles and showed a rugose surface both on top and bottom. A thin bed of oxidized red ash separated it from the lower flow. In the west wall of the trench, steam issued from between the individual flows, coloring the wall yellow with iron and other salts. In the east wall glowing lava could still be seen in the cracks, about which a white sublimate with a saline taste was deposited.

After this period of lava activity, the cone again passed into a relatively quiet stage, with the eruptive column reduced in size but without the heavy explosions that presaged the advent of new lava flows (pl. 31*A*). The eruptive column frequently carried little ash and rose in lazy cottony volutes and apparently consisted largely of steam. Activity continued in this erratic manner until October 15, when a new phase of activity was about to set in.

SUMMARY OF QUITZOCHO PERIOD

The Quitzocho period may be defined as that period connected essentially with the activity of the original primitive or Cuiyúsuru vents. This period continued from February 21 to October 19, when the principal activity shifted to another locus, the Sapichu[17] vent. The first phase of this period, from February 21 to March 18, was devoted largely to the building of the new cone by the heavy expulsion of bombs. Explosive activity was continuous, rather variable but usually violent. Little ash fell, but great quantities of bombs were ejected, and during a brief period of 25 days the cone grew from a small mound of only a few meters elevation to an edifice about 200 meters high.

The first flowing lava of the new volcano probably reached the surface early on February 21, or even during the night of the 20th, perhaps 8 hours after the initial outbreak. This lava flow, here called the Quitzocho flow, issued in erratic surges from one of the vents in the crater. When lava flowed, the new and weak cone was easily breached by carrying away the wall to yield a horseshoe-shaped cone. When the surge halted, the breach was rapidly repaired. The configuration of the cone varied almost daily with the changes in the eruptive activity of the volcano.

A sudden change to a heavy cineritic phase began on March 18 when the explosive activity that yielded abundant bombs changed to a heavy emission of ash, which spread over a wide area and destroyed cultivated fields and forests. A continuous eruptive column rose to a great height, as high as 8,000 meters above the cone. Two brief outbreaks of lava from a vent on the south flank of the cone yielded two relatively small flows, the Pastoriu and the Mesa del Corral flows. Both outbreaks of lava were preceded by a partial breaching of the cone.

This heavy cineritic phase ended on June 9 when a period of variable activity began with erratic eruptive activity in the crater and recurring lava flows from ephemeral vents on the northeast flank of the cone. When the cone was partly breached preceding these flows, a large sector of the cone was partially carried away to form a high terrace and a greatly weakened north side of the cone. Lava flows from these ephemeral vents covered portions of the earlier flows as well as new ground to the north, northeast, and northwest of the cone.

Three lava vents were intermittently active during this period. There were two short flows from a vent on the south flank of the cone and one small flow from the west flank of the cone. But the greatest

[17] The authors prefer the spelling Zapichu, following Gilberti, Diccionaria de la lengua Tarasca; Basalenque, Arte de idioma Tarasca; and other authorities; but for the sake of consistency have agreed to follow the spelling used in previous chapters of this bulletin.

lava activity came from vents on the north flank of the cone. The flows of this period are tabulated below:

Chronology of lava activity, February 21–October 18, 1943, flow

Date	Flow	Vent
Feb. 21	Quitzocho	Cuiyúsuru.
Mar. 18	Pastoriu	Ahuán.
Apr. 17	Mesa del Corral	Do.
June 10	Brief, unnamed	Cuiyúsuru.
June 10	Quitzocho ridge	Do.
June 12	Parícutin	Do.
June 14	Lagunita	Do.
July 27	Quitzocho	Do.
July 29	Tititzu	Quitzocho ridge.
Aug. 26	Short, unnamed	Do.
Aug. 26	do	Taquí.
Sept. 18	do	Do.
Oct. 2	do	Ahuán.

The outbursts of lava, in all cases, were immediately preceded by rapid and startling changes in the activity in the crater. The high, heavily ash-laden eruptive column shrank rapidly in size, decreasing to the emission of tenuous vapors and the ejection of large viscous bombs, irregular in shape, accompanied by heavy explosive noises. This type of activity was followed, within 12 hours, by an outbreak of lava from the base of the cone, or its lower flanks, immediately followed by a return to normal of the eruptive activity.

Usually the appearance of flowing lava was immediately preceded by a collapse of a segment of the cone, brought about, as one could see in the development of the Quitzocho ridge, by the lava stream carrying the incumbent cone material away from the cone. Such events took place on April 17, Mesa del Corral flow; June 10, various flows of that period and the injection of Quitzocho ridge; July 17, no visible lava flow; July 27, injection into Quitzocho ridge; early August, injection into Quitzocho ridge and the Tititzu flows; and August 26, small collapse, no flows. The sequence for events during an outbreak of lava is as follows:

1. Normal heavy eruptive column.
2. Rapid change to heavy crater explosions, with diminished eruptive column.
3. Rafting of segment of cone.
4. Appearance of flowing lava.
5. Return to normal eruptive column.

338669 O—55——6

An event of unusual interest during this phase, was the growth and development of the Quitzocho ridge by the injection of lava or the passage of a lava flow below the ash cover. It received successive increments of material on June 10, July 27, and August 26. It yielded four relatively small lava flows from its flanks and grew to be one of the prominent topographic features of the volcano.

A cursory comparison of the volcanic activity during the early phase of this period with later phases might suggest that the fundamental nature of the eruption had changed—that the change from heavy bomb explosion to heavy ash ejection and the change from a horseshoe-shaped apparatus to a symmetrical cone was due to a change in the character of primary activity. A consideration of these changes has led us to the conclusion that the fundamental activity in general remained unchanged and that the apparent change in the nature of the volcano's activity was due to the increasing incumbent load of ejectamenta forming the cone. After the first month's activity the cone had grown so large that flows which previously would have broken out at the base could no longer completely breach the walls and now carried segments of the cone only a short way. The change from a heavy bomb stage with little ash to a heavy ash stage was the result, in part, of an increasing degree of choking of the vents in the crater. In the early stages, when bombs were the principal ejectementa, the rising gases were free to escape from the rising column of lava. With the accumulation of debris to form a more stable cone, the exit of the gases was impeded by ash and other debris that slid from the inner slopes of the crater or fell back into the vent, thereby giving rise to a heavily charged eruptive column. We frequently found bombs that showed considerable attrition, even to the extent that some became as round as cobbles, owing to their repeated ejection from and descent to the throat of the volcano. Where two or more vents acted differently, as in mid-June when the south vent yielded steam with little ash and the north vent ejected a column heavily charged with ash, it was quite apparent that the vent was fairly open in the first case and seriously choked with accumulated debris in the second.

Taking into consideration this modifying effect of the growth of the cone upon the eruptive activity, there appeared to be no essential change in the nature of the rise of the lava in its conduit from the first and through the succeeding periods.

We have made calculations of the amount of solid material emitted by the volcano during the period February 20 to October 20, 1943, both as lava and as ejected ash, lapilli, and bombs. The bases for these calculations are the areal extent of the lava flows and ash falls, as measured on the map prepared for us by Sr. Adán Pérez Peña;

estimates of the thickness of the flows, as viewed in the field; and an estimate of the porosity percentages of the various products. For ash and fine lapilli, measured and weighed volumes indicate that fairly well settled ash has a weight of 1,500 kilograms per cubic meter and fine lapilli, 1,250 kilograms per cubic meter. Although well packed and settled by the continuous movement, the cone with its fine and coarse pumiceous ejectamenta has been assumed to have a porosity of 60 percent; while the flows, with their vesiculation, interflow rubble, and fissuring are calculated to have a porosity of 50 per cent. The figures so arrived at are contained in the following tabulation:

Weight of ash and lava, Parícutin

[February 20–October 20, 1943]

	Millions of metric tons
Quitzocho flow	6
Pastoriu and Mesa del Corral flows	3
Parícutin flow	2
Lagunita flow	10
Quitzocho ridge	6
September–October flows	3
Ash:	
Cone	110
Mantle	313
Total	453
Average rate per minute ... metric tons	1, 300
Average rate of ash per minute ... metric tons	1, 200

While these figures are only approximate, they do indicate the great preponderance of ash over lava during the first stages of the volcano, there being roughly 10 more times more ash than lava. The average rate of ejection of ash, 1,200 metric tons per minute, gives some measure of the tremendous explosive activity of the vent. With an average rate of explosion of about 15 per minute, the average weight of ejectamenta in each burst is about 80 tons.

It was during this period, the Quitzocho, with its heavy ash and bomb falls, that the new volcano built its cone. As was later seen, the increment of ash and other ejectamenta upon the cone from this period on was offset by rainwash, slumping and other degrading processes. The original vent in Pulido's cornfield on February 20 had an altitude of about 2,400 meters above sea level. At the end of the Quitzocho activity, the highest point on the crater rim reached an altitude of about 2,725 meters above sea level.

The early growth of the cone appeared extraordinarily rapid; from 6 or 8 meters on the morning of February 20 to 30 meters or more at midafternoon of the same day and 167 meters 6 days later. Naturally, as the cone grew larger, the same quantity of ejected material spread over an increasingly larger area of cone, effected a decreasing increment in elevation. Nine months after the initial outbreak the cone had reached maturity.

On a number of occasions we timed, by stopwatch, the rate of fall of the visible bombs from the highest point of their flight to an elevation of the crater rim. The maximum time interval so measured was 16 seconds. From this rate of fall, the maximum elevation of distinguishable bombs is 4,000 feet (1,250 meters), and the speed with which these bombs left the explosive vent, 550 feet per second.

SAPICHU PERIOD

SAPICHU VENTS

The 7-month Quitzocho period, from March 18 to October 17, was followed by a 2½-month period in which the principal activity shifted to a subsidiary vent that broke out near the northeast base of the cone and much reduced the eruptive activity of the main crater. A small cone, built up about this subsidiary vent, was named Sapichu by the Tarascan inhabitants of the area, from the Tarascan word "sapichu" (little or small). This period of activity we shall call the Sapichu period. The continuous eruptions of Sapichu yielded one of the most spectacular sights to be seen during the history of Parícutin.

On the 17th of October, earth tremors, which were frequent although weak during the preceding phase, greatly increased both in number and intensity until they became almost continuous; and the dishes in the refreshment stands on Cerro de Jarátiro rattled almost continuously. These trepidations continued until the night of October 18. According to our informant, Sra. Aurora Cuara Soto, at 11 p. m. a series of vents suddenly opened, aligned in a northeasterly direction. This new outbreak began with a heavy explosion; bombs and lava fragments were hurled into the air from the new vents to a height somewhat greater than the main cone. According to Manuel de la Vega, Mexican alpinist, the explosion was immediately preceded by a strong earth shock and followed by subterranean noises. At the same time, a fissure several hundred meters in length formed in the Quitzocho and the incumbent Lagunita flows, and five or more vents opened up, spouting incandescent lava many meters into the air (pl. 31*B*). Sra. Aurora Cuara estimates that the line of vents extended for 300 meters. From these vents, "flames" of bluish yellow and orange arose. The accompanying noise was like that of a starting railway locomotive, a noise we had come to associate with escaping gases from a rising lava column, usually at the initiation of a new flow or lava surge. Meanwhile the crater of the cone ceased ejecting bombs, and the eruptive column changed to a dense black ash column, with, she said, "flames [incandescent ash] that covered all the horizon."

According to Sr. Arno Brehme, the vents followed the crest of a low domed ridge fissured parallel to its axis, suggesting that the lava of the Lagunita flow had first been elevated by injection. De la Vega reported 5 vents. Brehme also reported 5; but Sra. Cuara, who from the vantage point of Cerro de Jarâtiro had an excellent view, saw 7. Three of these, in the lava field northeast of the base of the cone, yielded steam, a few small bombs, and no ash. An orifice on the flank of the cone was more active, ejecting viscous lava in small quantity to form a small mound. But the principal vent, which was to persist and build a cone, was in the lava field near the base of the cone and ejected numerous viscous lava bombs, and a wide lava flow issued from the vent. Ordóñez (1943) reports that three vents remained in activity on the second day. One was active only at long intervals. A second, more active, with a low cone half open toward the north, was situated on the flank of the cone. The third vent, lying directly northeast of the second vent, was the largest and was partially inclosed in a horseshoe-shaped "cone." This third vent showed explosive bursts at intervals about a second apart and threw up a column of viscous lava bombs to a height of 120 meters, accompanied by moderate to formidable explosive noises.

On October 21 the main new vent was in full eruption, with explosions following one another in rapid succession at a rate of 65 per minute (pl. 32*A*). The ejected material was stretched viscous masses of lava that were torn into several discrete bombs during flight. A cone had begun to form by the accumulation of ejected material about the vent, but at this stage inclosed only an arc of about one-sixth of the circle to the southwest of the vent. This wall was steep and about 15 meters high. A second orifice, about 50 meters from the main vent, erupted at intervals of 5–30 minutes with a sound like a locomotive starting. With each period of activity it emitted a few puffs of yellowish-brown fumes, or dust, and then subsided. About 20 meters southwest of the main vent was a slitlike orifice, aligned and sloping toward the main vent, that erupted every 4 or 5 minutes, throwing out viscous lumps of lava which plopped onto the ground. A white steaming crack extended from the crater rim to about two-thirds of the way down the slope of the cone.[18]

At the end of 4 days of activity the small upper vent on the flank of the cone ceased its explosive activity, but its locus remained evident for many days afterwards as a small ash-covered knoll, stained yellow and white with fumarole products and from which arose a gentle curl of vapor.

[18] From notes of David Gallagher, U. S. Geological Survey.

The remaining vent, now christened Sapichu, continued to eject viscous bombs without cease and to build its cone. Great quantities of lava continued to pour from its throat in surges that were sporadic but continuous enough to maintain an open breach on the northeast side of the new cone. At no time in its history did Sapichu assume a completely conical shape. From the very beginning to its last day of existence, it was always a lune-shaped "cone." During Sapichu's first days its crest was of irregular and changing outline, depending on the vagaries of explosion and slumping. On October 23 it had a low, semicircular form with a ragged crater rim. This rim was somewhat lower at the head of the cone where the ejected bombs from the vent scoured the walls. This sag was flanked by two small earlike peaks. As the cone grew and gained stability, it assumed a more regular form, eventually becoming a smooth horseshoe. A series of parallel steaming cracks formed on the main cone above this vent.

Ordóñez (1945) states that on the morning of October 23 (8:05 a. m. October 22, according to Gallagher [19] and Storm [20]) a new vent opened on the outside flank of the main cone, about 50 meters below the northeast rim of the crater (pl. 32*B*). From it, dense black ash arose in small cauliflowers, with a noise like the escape of air under high pressure. The actual vent had a diameter of about 6–10 meters. Its eruptive column rose 80 meters and mingled with the vapors from the main crater. Gallagher describes the eruptions as exploding about 60 times per minute, yielding huge volumes of dark-gray ash, and the column as rising in cauliflower volutes. The outbreak continued, with a few pauses of variable intervals, until early afternoon. Gallagher places this vent on the line of the steaming crack observed 2 days earlier on the slope of the cone above Sapichu.

The area around this new vent, or chimney, and the cracks below it later developed by subsidence into a smooth-sloped swale of hot and muddy ash, spotted with patches of white, yellow, and greenish salts.

ERUPTIVE ACTIVITY OF SAPICHU

From the first day until Sapichu began to show some diminution in its explosive activity in late December, eruptive activity was notably constant and regular. The lava flow, although showing some variability, was continuous. Explosions from the vent occurred at fairly regular intervals, almost one each second, hurling viscous lava to a maximum height of 300 meters. These bombs appeared incandescent even during daylight. This fountain of incandescent bombs illuminated the environs of the cone at night and presented a magnificent spectacle. With rare exceptions the ejected bombs were all of one type, an inflated vesicular sponge that was shiny black inside and dull,

[19] From notes of David Gallagher. [20] From photographs by Lyn Storm.

dark olive brown outside. The larger bombs were sufficiently viscous to flatten somewhat upon impact with the ground, and coins could be forced into them to yield souvenir pieces. This type of bomb was so characteristic of Sapichu that we referred to them and other similar ejecta as Sapichu type. A very rare and curious type of bomb, not observed at any other time, was a dense nodular mass without gas cavities. They showed small olivine phenocrysts in an aphanitic groundmass.

The characteristic ash of Sapichu was dark brown, very spongy in texture, and frequently of a dendritic structure. Fine filaments of glass were common in this ash. Bombs of xenolithic material were more common in the ejectamenta of Sapichu than in that from the main cone and showed a greater degree of fusion. Ordóñez [21] reports that on November 20 the amount of this ash was so great that the ground around Sapichu was covered with a light-colored mantle resembling snow, but we were unable to find such a layer by digging a pit in the ash. These erratic bombs are evidently fused masses of diorite from the underlying basement rocks. The smaller fused fragments were very vesicular and snow white. They usually showed unfused quartz grains within the vesicular masses. Larger fragments were similarly fused, although some of the larger bombs were only partially so.

In remarkable contrast to the activity of the main cone, Sapichu showed no visible eruptive column, other than the ejected bombs. Bluish-white vapors, or rarely rusty-brown fumes (or dust), rose from the vent but were soon dissipated into the atmosphere. If atmospheric conditions were propitious, the emitted vapors condensed some hundred meters above the cone, forming a "tail" which widened upward into a white cumulus cloud (pl. 33*B*). It was evident from the volume of these clouds, some of which covered a large part of the visible horizon, that a great quantity of condensable vapors was being discharged from the eruptive vent. The rare times when one observed ash in the rising column were short intervals following a brief quiescence, usually no longer than 10 seconds, during which a thin brownish or dense black column arose to a height of a few hundred meters. During these brief and rare periods a vesicular red or black cokelike ash fell sparingly.

No lightning discharges were observed in the emissions from Sapichu.

During Sapichu's period of eruption the crater of the main cone showed very reduced activity (pl. 33*A*), and there were times when no visible vapors arose from its crater. Two vents were still apparent: a central one, which sometimes showed mild explosive activity, and one near the northeast rim, from which only languid white clouds arose.

[21] Oral communication.

Few incandescent bombs could be seen during the nights. Such bombs as fell outside the crater were an assorted lot: irregular aphanitic fragments, scoriaceous lumps, welded masses of small agglomeratic fragments, and a few round concretionlike bombs of aphanitic lava, suggesting that in spite of its reduced activity viscous lava was still present in the throat of the vent. The noises from the crater, too, were much diminished, the only sound audible at the camp being a subdued thundering rumble.

The following discussed days may be considered typical of the period of the life of Sapichu.

November 28, 1943.—The cone of Parícutin was regular except for a smooth steamy swale that extended down from the northeast crater rim. The main crater showed two vents, one in the center of the cone and the other near the head of the swale. Activity in both vents was much reduced, and there were times when nothing rose from the crater. A column of vapor, with little ash, ascended lazily, with little or no explosive force. Only white fleecy clouds of water vapor ascended from the northeast vent, usually to a height of not more than 50 meters. These emanations, white and billowy, like cumulus clouds, indicated a constitution of almost pure steam. The column from the south vent was sometimes white but frequently pale gray, indicating some admixture with ash. Rarely, cauliflowers or volutes arose lazily from this vent. Light vapors rose from cracks in the ash in the swale on the northeast slope of the cone.

Bomb bursts were rare and weak, and almost nothing fell upon the outer slope of the cone. This contrasted strikingly to the highly explosive and spectacular eruptions of the preceding few months when great columns of incandescent bombs rose to great heights and showered over the surrounding terrain. Now hardly an incandescent stone was seen above the crater rim.

Sapichu at this time was about 80 meters high and continued to maintain its horseshoe shape open to the northeast, in the direction in which the lava flowed.

The explosive bursts of Sapichu followed one another in rapid succession, averaging about one a second, with stronger explosions at irregular intervals, several per minute, that shook our cabin strongly. The explosions threw up a spray of viscous lava fragments that appeared incandescent even in the daylight. A column of tenuous vapor of gray brown (the color of nitrous oxide fumes) rose from the crater. With these vapors were fumes of bluish white that soon dispersed through the slowly rising column of gases. No condensed water vapor was visible.

The ejected blocks were of all sizes, up to about 2 meters across, and were plastic, changing shapes or being torn apart in their flight through the air. The solidified bombs were almost all of one type—irregular in shape, frequently rather round or flattened, very slaggy, almost spongily vesiculated, and powdery cinnamon brown on the outside and shiny blue black on the inside.

The lava flow was very large and had the appearance of a jumble of blocks and clinkers. Little of the moving lava below the clinkers was visible.

Whirlwind columns formed over the hotter portions of the lava during the day, some rising to a height of several hundred meters and persisting for 10–15 minutes.

For a few minutes in the morning, segments of compression waves, owing to the explosions, were visible in the rising vapors from the vent, following each other in rapid succession. Occasional weak waves were observed during the day, but none was seen at night.

Occasional flashes of lightning were noted in the eruptive column of the main Parícutin crater, and there were rare bursts of incandescent ash and very few bombs.

November 29.—Ash clouds from the main crater rose lazily and drifted to the northeast, but the activity was erratic and the cone sometimes inactive, with no ash and almost no steam emitted.

Sapichu showed its usual constant activity, except for one very brief pause of about 10 seconds, during which some ash rose from its vent. The explosive sounds in the vent came in a series of rapid sharp puffs interspersed with loud blasts. We timed the rate of fall of the highest bombs; these took 9 seconds to fall from their highest point to the ground (400 meters).

At 6 p. m. the rising vapor column from Sapichu showed some condensation about 500 meters above the vent, where it formed a small cumulus cloud.

November 30.—Strong winds from the southeast raised dense clouds of dust, and there were heavy clouds in the east, southeast, and south; fewer, to the north.

During early morning a low gray vapor column rose from the main crater, changing at 11 a. m. to pure-white vapors. These white vapors continued until 2 p. m. when they again changed to a dense light-gray cloud that spilled over the west rim of the crater and settled to the base of the cone. At this time we encountered a light fall of mud. In about 15 minutes fog settled over the cone, almost obscuring it from view; and a faint odor of hydrogen sulfide was perceptible.

The activity of Sapichu was constant and regular. Besides the usual bombs, it threw out a pale-olive-brown dendritic ash, with a very little black and red cokelike scoria, and some snow-white vesicular fragments of fused diorite. There appeared to be two extremes of explosion. One, directed upward, yielded a bomb column shaped like a compact cedar tree and was presumably from explosions within the vent; the second was a burst of bombs radiating in all directions and apparently from explosions at the surface. By far the greater number were intermediate in form, yielding a fan-shaped burst of bombs. During midafternoon, there were several short bursts of black ash from the vent. These ash bursts always occurred rarely, followed a brief pause in the explosive activity in the vent, and contrasted strikingly to the almost ashless normal column.

At a station on the northwest flank of the main cone and about 150 meters from Sapichu itself, distinct tremors could be felt following each explosion. The maximum intensity of these tremors followed a zone from the vent of Sapichu to the main crater. At this same station I could detect a faint odor of sulfur dioxide in the fumes wafted from Sapichu.

At 2:45 p. m. a series of compression waves was apparent in the rising gas column, although the explosive activity in the vent showed no increase in intensity from its normal condition.

During the night, we felt many weak tremors at the cabin and occasionally detected an odor of hydrogen sulfide.

December 1.—The morning was cloudy but with little ash in the air and no wind.

The vapor column of Sapichu rose to a height of about 1,000 meters and condensed to a dense cloud that hid the sun. The eruptive column of the north vent of the main cone was white and billowing, followed in the evening by a dark-gray column from the south vent.

In the afternoon a strong wind raised such dust that the volcano was obscured from view, and at night it rained.

December 2.—Most of this day was spent south of the cone. Returning, we came to Sapichu about 3 p. m.; and, the wind blowing towards us from Sapichu, we could distinctly smell sulfur dioxide. Sapichu continued to throw out its usual type of bomb and characteristic dendritic ash.

From the slopes of the main cone, we could look down upon a fumarole yielding copious steam and located about 100 meters from the base of Sapichu. With almost every explosion from the vent of Sapichu, a compression wave could be seen distinctly through the fumarole's steam. During the evening and early night, fog drifted in from the west and hung about 100 to 200 meters above Sapichu. Numerous compression waves were visible flashing through this blanket of overhanging vapor.

Activity from the main cone was very weak until evening when there was an increase in the volume of vapor and ash.

December 3.—The sky was overcast with dense white clouds, and there were showers during the day.

Rather dense gray vapor clouds came from the south vent of the main crater, and billowy white vapor clouds, from the north vent, and wisps of vapor drifted about the upper part of the cone; the eruptive column rose lazily and without bombs.

There was no change in the eruptive activity of Sapichu. The vapor column condensed into a gray cloud about 700 meters above the vent.

December 4.—A trip was made with Luis Aguilar to the east of Sapichu, and a place was found along the edge of the flow where the lava front could be climbed to the top of the flow. The surface of the lava was a jumble of dark-gray blocks and clinkers mottled with oxidized brick-red patches. From this desert of rocks rose an occasional crag or irregular ridges of twisted lava.

The lava front differed from place to place. Usually it was a steep slope of advancing rubble made up of gray or red lava fragments which rolled down the slope as the front advanced, raising clouds of pinkish-brown dust. Moving lava could be seen between large blocks of chilled lava, bulging slowly and fissured by incandescent cracks. Where massive lava was exposed, it formed dark-gray twisted blocks with a harsh pimpled surface.

Here and there one saw on the surface of the flow huge craggy masses of oxidized, loosely consolidated blocks of lava making up a rubble that resembled a coarse tuff. These appeared to result from the disintegration of chilled lava blocks. There were also mounds of welded bombs, sometimes a kilometer or more from the vent, that were portions of the cone of Sapichu carried away by the moving lava stream.

On the trail back, we met Sr. Arnaldo Pfeiffer, of Morelia, and Sgt. José Rosales, stationed at San Juan Parangaricutiro, on their way to the summit of the cone, which they reached about 4 p. m. Upon his return, Sr. Pfeiffer reported that the swale below the northeast rim of the crater was muddy and hot with rising steam, necessitating a wide detour to avoid this impassable quagmire. A broad area covering this portion of the cone was streaked and colored with patches of orange, yellow, and white salts. This area, it should be noted, was the locus of the ephemeral vent of October 21. Sr. Pfeiffer reported that the crater rim was sharp. He was unable to see into the crater because of the copious emission of steam.

December 5.—There were scattered clouds and strong southeast winds today and more than usual activity from the south vent of the main crater, with a billowing light-gray column, sometimes rising to a height of 500 meters and then drifting toward the northwest. The north vent showed only mild activity, consisting of low drifting vapor clouds. Activity from Sapichu was normal and regular.

In the afternoon we went to the east side of the lava flow, accompanied by Mr. Igor Sikorsky and Sr. Manuel Guzmán. We climbed the lava front and were able to approach within 300 meters of the open flank of Sapichu and to observe the character of the cone and the nature of the activity. The interior of the crater was a steep wall of semiconsolidated lapilli. The walls were continuously bombarded by molten bombs, and the lower walls and flow were veneered with viscous lava, which flowed slowly back to the vent. Occasionally a large slab of very viscous material would slide from the wall, exposing an interior of golden-yellow incandescence. There was but one explosive vent from which the lava issued continuously as a flow, and the escaping gases hurled viscous incandescent masses of lava into the air as an almost continuous fountain of "fire." The vent emitted copious white fumes.

The harsh grating roar of the explosions once ceased for a few minutes, and a tenuous brown dust billowed up, but incandescent bombs continued to be ejected without change. One tremendous blast threw huge masses of viscous lava against the crater walls.

In front of the vent was a breached wall, made up of welded incandescent bombs. It was slowly broken into huge segments which were carried away by the slowly moving lava stream, riding along like ships on a river.

Compression waves were visible in both the vapors rising from the crater and in the steam of nearby fumaroles and could be correlated distinctly with the explosions in the vent.

According to Luis Aguilar,[22] Sapichu was still in continuous activity on January 5, 1944, but the force of its explosions gradually diminished until it was a mere vent of spattering lava. On January 6 the activity ceased completely.

CRATER OF SAPICHU

On January 8 we entered the crater of Sapichu for the first time and approached within 30 meters of the vent itself. The orifice was about 1 meter across and located upon the summit of a low lava mound. Sparse bluish-white vapors arose from the orifice, and occasionally a sudden belch of gas threw out a few small incandescent fragments of lava.

On January 10 activity in the crater of Sapichu was completely extinct, and we were able to examine the whole apparatus in detail. The vent, about 1 meter in diameter, was at the base of the south inside wall of the cone, which was about 50 meters high. Peering into this

[22] Oral communication.

vent to a depth of about 2½ meters, we could see tenuous fumes issuing from incandescent crevasses, but there was no distinct odor about the orifice. The lava of the vent seemed distinctly massive.

The walls of the crater were made up of semicompacted bombs and had angles of slope up to 60°, but rocks were almost constantly sloughing off to form a talus fan at the base. Above the eruptive throat and to the right was a low cavelike overhang. This cave and the walls immediately above the orifice were veneered with smooth massive lava for a distance of about 15 meters above the vent. Above this were steeply dipping lenses of massive rock 15 to 25 centimeters thick, evidently huge masses of viscous lava thrown against the walls during violent explosive bursts. There were also steeply inclined slickensides where slabs of viscous lava slid off the walls, as we had observed on December 5. At the horseshoe ends of the cone, the walls were made up of loosely compacted broken bombs. The bomb material was coarsely stratified with the beds dipping toward the axis of the horseshoe. The eastern limb of the horseshoe was broken into blocks and separated by crevasses where the flowing lava had begun to carry away blocks of the walls.

The lava in the crater consisted of twisted slabs of semivesicular rock, covered by scoriaceous and slaggy bombs. Several terraces were discernible, evidence of several distinct lava surges.

With the cessation of the eruption, activity in Sapichu completely ceased and was never resumed. Not even fumarolic vapor arose from the vent. In time the sloughing of the walls reduced the crater to a semifunnel, with walls of about 35°.

In November and December 1947, lava flows from the Taquí vents covered the last remaining traces of the Sapichu cone.

The lava flow of Sapichu greatly exceeded any of the previous lava flows; in fact, exceeded all the previous flows combined. It covered an area of more than 3 square kilometers and had an estimated weight of 38.5 million metric tons. It completely covered the Lagunita flow (June–July 1943) and a part of the Quitzocho flow (February–March 1943) as well as the lands of Corúnguaro, Turímbaro, Jarátiro, Titítziro, Churingo, Terúpicua, Tipacuaro, Cheraquijando, Piedra del Sol, Nitzicátaro, Chorétiro, La Lomita, and El Pajarito, extending to and in places crossing the San Juan Parangaricutiro–Uruapan road (pl. 43*B*).

The lavas showed the same characteristics as previous flows, both in type of material and in their advance as a steep-walled rubbly front. The surface of the lava flow was the usual confused jumble of dark-gray blocks, profusely mottled with oxidized patches of brick red. Spires or towers of breccialike material rose here and there above the general level of the flow, and irregular ridges of twisted lava could be seen.

Only a few persistent fumaroles developed in the Sapichu flow. Most of these were localized along a scarp where the Sapichu flow poured over the old front of the Lagunita flow onto the ash-covered fields of La Lagunita (pl. 45*A*).

The ultimate front, at the San Juan Parangaricutiro–Uruapan road, about 3 kilometers northeast of its vent, formed a scarp about 10 meters high (pl. 43*B*) made up of blocks of disintegrated lava and scoriaceous clinkers of all sizes. The largest block observed had a volume of about 300 cubic meters. Crags of solid lava protruded from the rubble but showed no flow surfaces.

With the cessation of activity at Sapichu, the main crater resumed its normal explosive activity; the eruptive column rose in successive cauliflowers with the ejection of considerable ash and bombs and the usual noises.

CRATER OF THE MAIN CONE

During the reduced activity of the main crater, the cone was ascended for the first time, by Sr. Arnaldo Pfeiffer, veteran alpinist of Morelia, on November 3; and Sr. Pfeiffer, accompanied by Sgt. José Rosales of the Mexican Army, stationed at San Juan Parangaricutiro, made another ascent on December 4. Pfeiffer reported that the area below the low northeastern rim was very muddy, hot, and steamy. The crater rim was very narrow, not more than a meter wide; but he was unable to see into the depths of the crater because of the copious vapor clouds that filled it.

On December 19 an ascent was made by Srs. Abraham Camacho and Celedonio Gutiérrez who reported that the crater was funnel shaped and its steep walls were covered with small and large black rocks. In the bottom of the crater were three small funnel-shaped vents, oriented east-west. Vapors issued from these vents, sometimes simultaneously, sometimes alternately. A large fumarole, located on the eastern wall of the crater, emitted abundant vapors. About this fumarole the walls were encrusted with white and yellow sublimates. At that time the cone had an elevation of 345 meters above the level of Quitzocho (Ordóñez, 1945).

Luis Aguilar and Sgt. José Rosales ascended the cone on January 5, 1944. At that time the crater had the form of a shallow dish. The crater contained five funnel-shaped vents, the principal one near the southwest edge of the crater. A very strong odor, described by Aguilar as the odor of the gases of the hornitos (hydrochloric acid), pervaded the crater; and there were abundant yellow sublimates within the crater. During their stay on the rim the volcano began to thunder and give off puffs of black smoke; whereupon they came down very quickly.

SUMMARY OF SAPICHU PERIOD

Sapichu and its accessory vents broke out along the line of the small fissure that appeared at Llano de Cuiyúsuru during the birth of the volcano on February 20. This apparent line of weakness includes, besides Sapichu and its accompanying vents, the main crater vent and the vents of the Mesa del Corral flows on the opposite side of the cone. This last vent, which we later called the Ahuán vent, became an important locus of later lava flows. This line was also a marked tremor zone. Sapichu, therefore, evidently occupied a position on one of the important fissures of Parícutin volcano.

Sapichu throughout its entire life showed only a strombolian type of activity, because the explosive activity took place at the summit of a continuously rising lava column where it was unimpeded by any overburden in the throat. In many respects Sapichu showed the characteristics of the main volcano during its early stage, but with these important differences: its explosive activity was less violent but more regular and its lava flow much larger and more regular. The greater explosive capacity of the original vent and the greater abundance of fumaroles in the Quitzocho flow suggest that the gaseous content of the Sapichu lava had decreased from that of the earlier flows. The quantity of ejected diorite blocks was much greater from Sapichu than from the main cone, and the blocks showed a greater degree of fusion.

Although there may have been some pauses in the emission of lava from the Sapichu vent, they were not directly observable, the flow of lava being essentially continuous. This is in contrast to the Quitzocho period when lava flowed from the main vent in frequent surges and even in individual flows. Because of this continuous flow of lava from Sapichu, its "cone" was never complete and always maintained a horseshoe shape; for the flowing lava stream continuously carried away the accumulating bombs from its northeast side. Masses of these bombs were later found a kilometer or more from the cone, where they had been carried by the lava stream. In the Michoacán basalt province, there are a number of such cones, some of which undoubtedly had a history similar to that of Sapichu.

This horseshoe shape allowed clear observation of the character of the explosions in the vent. These explosions took place at the top of the rising lava column or at depths of no more than a few meters below the surface. The explosive activity also clearly showed that a vent free of accumulated debris or of slumping from the sides of a funnel-shaped crater yielded an eruptive column free of dense ash or triturated material. The ejectamenta from the freely rising lava column consisted of vesicular spongy bombs or shredded ash. The eruptive column yielded by such a rising lava is tenuous, consisting largely of invisible water vapor that, when atmospheric conditions are appropriate, condenses as cumuluslike clouds far above the vent.

One of the more remarkable features of Sapichu was the relatively small diameter of the vent. The lava vents in later flows were not large, but in none was it so small as at Sapichu. Its vent, hardly more than 1 meter in diameter, was capable of supplying a lava front more than a kilometer across and about 5 meters high and maintaining this front in a state of continuous, if slow, advance.

This lava flow was of the same nature as the previous flows. The total area covered by the Sapichu lavas was found, upon measurement, to be 3¼ square kilometers. The lava differed very little, chemically, from the lava of the previous period.

Although it was evident that Sapichu occupied a position on a fissure, it showed no apparent change of location or movement along this line and remained fixed throughout its life. The fact that its cone showed no appreciable change, other than those incident to its growth, tends to confirm this observation.

During the life of Sapichu, activity in the main crater was considerably reduced, yielding a light-gray eruptive column from a central vent and white vapors from a vent near a northeast rim. For a day during the early period of Sapichu, a vent on the northeast slope, corresponding to the lava vent of the Lagunita flow, sent up an intermittent eruptive column.

TAQUÍ PERIOD

TAQUÍ VENTS

With the cessation of eruptions at Sapichu, the locus of active lava vents changed to the southwest base of the cone, and the eruptive activity of the main crater greatly increased. By January 8, when the last dying gasp of Sapichu was observed, the main crater was again in full activity, with a billowing eruptive column rising in well-formed cauliflowers to considerable heights. Ash began to fall again in perceptible amounts in the form of brownish corky grains, cokelike fragments, or as small flaky spalls. Bombs, too, again fell on the cone in abundance. These consisted of dense, rounded congealed masses, semiscoriaceous platy masses, or irregular blocks of agglomerate of partially welded fragments. Explosive activity appeared to be localized in the southwest, or main vent of the crater. Explosive noises were rare, the sounds accompanying the activity being the surflike noise characteristic of heavy bomb activity.

About midnight on January 7 a bright-pink reflection appeared over the southwest base of the cone, indicating the presence of incandescent lava in that vicinity. The next morning revealed 2 new lava vents from which 2 active flows issued (pl. 35*A*). These vents were, as near as we could determine, at the locus of the small and short-lived vent of August 26, 1943. They were destined to be the most persistently active of any of the lava vents and to yield the greatest of Parícutin's lava flows. The 2 vents were about 25 meters apart and separated by a crevassed and bomb-spattered septum of congealed lava. The north orifice occupied the head of the narrow steep-walled trench formed by levees of congealed lava. This vent was surrounded by an aureole of spatter bombs. The lava in the vent was in a state of continuous ebullition, the incandescent lava spattering up to a height of 10 meters or more; and incandescent lava coursed rapidly, at an estimated rate of 1 meter a second, down the levee-bordered trench. The second, or south, lava vent, also at the head of a narrow trench, was more erratic in its behavior, sometimes spattering violently and sometimes flowing quietly but copiously down its self-made channel. There was an apparent connection between these two vents. When the south vent entered a state of violent ebullition, the activity of the north vent diminished or was even reduced to a quiet flow. From both vents and the flowing lava, bluish fumes arose, sometimes tinged with brown; and a strong odor of hydrochloric acid was evident about the vents. These vents we called the Taquí vents; and the flow that issued from them, the Taquí flow.

Above the lava vents was a bulge in the slope of the cone, surmounted by a narrow terrace about one-third the way up the cone. This smooth bulge of ash was traversed by a series of small cracks from which white steam issued continuously; and the whole bulge was moist with condensed steam, contrasting with the dry ash slopes surrounding it. In the ash on the terrace directly above the south lava vent was an orifice, about 3 meters in diameter and of unknown depth, from which issued dense white steam clouds.

The lava as it flowed from the vents changed rapidly from bright incandescence to a black stream dappled with glowing spots. Overlapping tongues of different stages of incandescence suggested that the emission of lava was not entirely regular and occurred in surges which followed one another in rapid succession (pl. 35*A*).

By the next day, January 9, the lava vents had changed some. The north orifice remained in constant ebullition, but the south vent flowed quietly, without spatter. The south orifice and a third vent observed behind it were separated by the rugose lava septum. This vent may have been present on January 8 but not sufficiently active to have attracted attention. It was very erratic in its activity, spattering lava at rare intervals. The steam orifice above the vents showed increased activity, giving off an occasional short burst of ash-laden steam, and in midafternoon showed an almost continuous

338669 O—55——7

activity, emitting a small ash-laden eruptive column and ejecting some small bombs (pl. 35*B*).

On the lower slopes of the cone, immediately south of the vents, the ash showed crevasses from which steam with a strong hydrochloric acid odor issued. The ash about these crevasses was stained with yellow alteration products. The north lava vent made little noise other than a faint "shu-uh shu-uh," and the south vent was quiet except for a rare low "chu-chu-chu." These sounds we had learned to associate with a rising lava column.

The lava from the two vents flowed rapidly down the low slope into the small valley formed by the cone and the east slope of the Mesa de Cocjarao. Although the general land slope was toward the north, a low ridge blocked the flow of lava in this direction, diverting the stream to the south and along the southwest base of the cone. The lava flowed freely from the vents and had a crude ropy surface, rather distinct in structure from any of the previous lavas, but the advancing front presented the characteristic jumble of clinkers and lava blocks shown by the previous flows.

Directly opposite the vents, on the lowest slopes of the Mesa de Cocjarao in lava-free terrain, we found a fissured and displaced ash zone about 200 meters long and 100 meters wide, extending from the lateral slope of the lava to the foot of the Mesa itself (pl. 34*B*). This zone had a strike of N. 50° E. Vertical displacements in the fissures of this zone did not exceed 30 centimeters. This unusual development of fissures in original, tree-covered terrain was unique in our experience at Parícutin. Later we were able to discover that this belt was also a zone of distinct tremors or, as we called it, a tremor zone. (See fig. 123.) This zone corresponds, as near as we could determine, with the direction of one of the original fissures that appeared on February 20, 1943.

On January 10 two distinct earthquake shocks were felt, one at 2:10 p. m. and another at 2:35 p. m. Later inquiry showed that these shocks were felt and recorded in Mexico City and that their epicenter was in the State of Guerrero and therefore had no close connection with Parícutin volcano. These shocks induced no evident change in the activity in the crater or in the lava vents.

TAQUÍ LAVA FLOW

According to reports, the first flow of lava from the Taquí vents continued until January 12. On February 6 these vents reopened and again poured out lava. By February 10 when we again visited the spot, we found it greatly changed from its condition of a month before. Many of these changes were evidently due to the accumulation of lavas, which was now great enough to submerge the vents of

Taquí, so that lava no longer issued freely at the surface. The lava continued to issue from its original vents but flowed beneath a thick crust of congealed lava, following irregular and wandering channels, to appear eventually at the surface several hundred meters from the locus of the Taquí vents.

During the month that had elapsed since the outbreak of lava at Taquí, the lava stream had advanced around the south and east sides of the base of the cone, filling the valley formed by the cone and the lower northern flanks of Cerros de Tancítaro. The lava front, about a kilometer long and 3 meters high, reached a point near Sapichu where it debouched onto rolling pine-covered terrain and ignited the trees in its advance through the forest. This lava advanced much like previous flows, with bulging lobes of viscous lava near the base and clinkers and blocks rolling down the front, stirring up small plumes of pinkish dust. Although the terrain over which the flow moved was of low smooth ridges and shallow arroyos, the advance of the front was rather uniform, its continuity broken only in three places, where tongues of lava showed a more rapid advance down some small arroyos.

From February 10–13 the eruptive column was dense and heavily laden with ash, and westerly winds carried the dust far to the east as a dark low-hanging cloud. Beneath this cloud the fall of ash was heavy and frequently came down as a mud that coated the leafless trees.

From a high point on Mesa de Cocjarao to the southwest of the cone, one could obtain a good view into the crater through the lower rim on the south side. The principal eruptive vent, somewhat toward the south wall from the center of the crater, gave off a continuous voluting eruptive column, in which lightning flashes were distinctly observable, even in daylight. To the north of this vent, there appeared to be a second orifice which exploded intermittently. Although ash billowed incessantly from the crater, only occasionally were there a few weak bursts of bombs. The accompanying noise was a low surflike rumble, with frequent low thundering rolls.

The ash that fell during this period consisted of a brownish shredded slag, porous fragments with a crust resembling pine bark, black coke-like fragments, and flat angular spalls.

This point marks the end of the first year of Parícutin's activity, the important stages of which are illustrated in plate 15 and lava flows in figure 122.

On March 1 when we again visited Parícutin, we found the lava field about Taquí vent greatly changed. The lava now completely filled the basin lying between the cone and the lower slopes of Mesa de Cocjarao and had surmounted the saddle that connected to two;

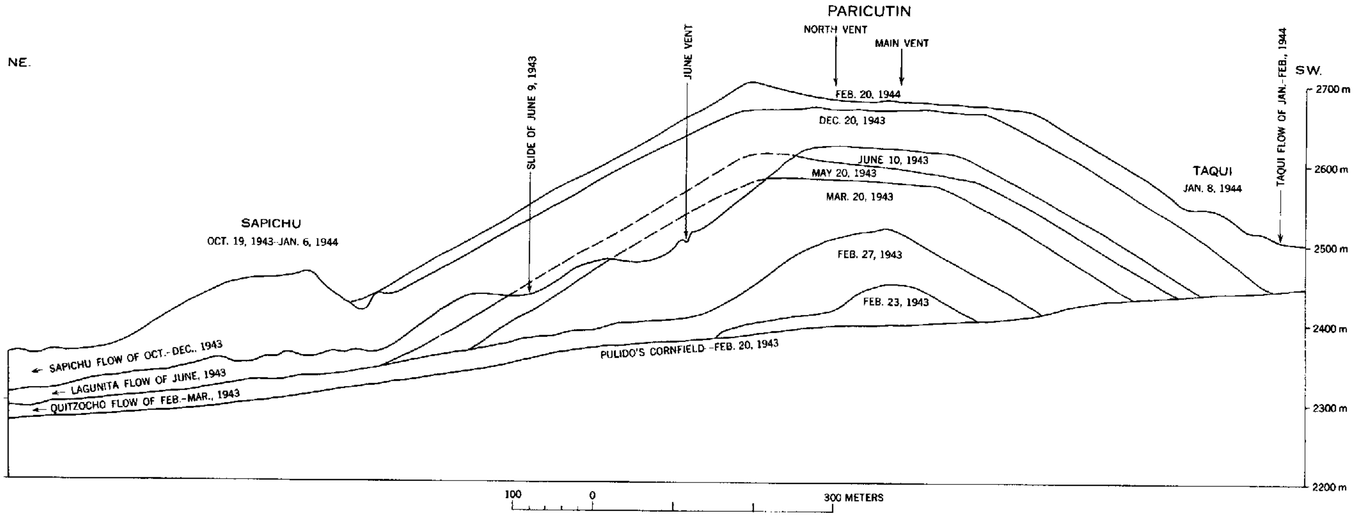


FIGURE 122.—Parícutin volcano, showing its important stages of growth during the first year, February 20, 1943, to February 20, 1944. Northeast-southwest cross section. During the first year's heavy cineritic activity the cone reached it full growth.

but, except for a short cold tongue of lava toward the north, the lava still continued its old course along the south base of the cone. In place of the active flowing vents, which were now deeply buried under the accumulation of flows, we found three steeply conical peaks with vertical shaftlike craters which Ordóñez (1943) called volcancitos (pl. 37*B*) and a great number of low irregular pinnacles of vesicular lava, or hornitos upon the congealed surface of the lava. Bluish vapors arose from summit vents of the volcancito, the irregular openings in the hornitos, and the fissures in the lava, and a strong odor of hydrochloric acid pervaded the vicinity. A wide area was brilliantly colored by an orange-yellow incrustation, imparting a weird, colorful beauty to this otherwise bleak and depressing landscape. A loud hissing, like the escape of steam from a number of vents, could be heard from some distance away.

At or about the locus of the original Taquí vent was a tall, slender volcancito, and nearby to the west was another asperous dome-shaped one, with a wide incandescent throat in its western flank. Still farther to the west was a steep conical volcancito with a glowing open mouth near its summit, and adjoining this was a smaller one, crusted on its southern side by a small rough tongue of lava. Nearby was an open cavelike throat in a low domelike eminence, which showed a number of incandescent crevasses and hissed particularly loud. About this line of volcancitos was a zone of fresh rough clinkery lava which had evidently only recently flowed over the older ash-covered flow. Beyond the volcancitos the zone of hornitos followed the course of the lava stream (pl. 36*B*). Here were dozens of these remarkable hornitos, but the abundant strong and choking fumes prevented an examination of them at close hand. Later we were able to study them in detail and even had the opportunity to see one grow. In addition to these pinnaclelike hornitos, one could observe numerous small warty excrescences of lava, usually less than 2 meters across, upon the old lava surface. Like the larger hornitos they showed small incandescent orifices, and they were, undoubtedly, low forms of the more conspicuous hornitos.

On March 3 we first observed flames from both the volcancitos and the hornitos. At dusk a faint-violet flame was perceptible, waving like a tenuous banner above the orifice of one of the volcancitos. Then similar flames were observed above the wide orifice of the largest volcancito and finally flames from orifices in the lava crust. Occasionally small incandescent stones were ejected from these vents. Within the area of the volcancitos, one could see that each incandescent orifice of the hornitos was likewise yielding flames and that the strong hissing, so apparent in the area, was due to the escape of the gases associated with these flames. The flames appeared pale violet in the light of dusk, but at darkness appeared pale blue and tinged at their edges with yellow. Above the large flames arose bluish-white fumes, or vapors. The flames from the volcancitos rose continuously in waving tongues, the larger ones rising to a height of 2 meters above the orifice. In the spacious orifice of the largest volcancito, the flames burst forth spasmodically at frequent intervals, like a flash or ball of pale fire. From the hornitos and low excrescences, the flames shot out with a continuous hissing like small blowtorch flames. The small vents from which the flames issued were lined with a thin coating of fused but viscous lava, which suggested a refusion of the lava by the heat generated by the burning gases.

On March 4 the crater had a symmetrical interior sloping to a single relatively small central vent. No evidence of a second vent was apparent. Small wisps of steam arose from the crater rim.

From the air, no flowing lava could be observed about the Taquí vent; but about one-half a kilometer downstream, a ribbon of red glowing lava apparently issued from beneath a lava crust. This stream showed continuous incandescence for about 300 meters, where it changed to a winding black river, moving over older gray lava.

The lava flow itself had not only advanced considerably since February but had also increased in thickness. The main front moved slowly, but at frequent intervals tongues of lava broke out from the rubble-covered face, forming outliers of twisted and crevassed black lava quite distinct from the more characteristic blocky form of the main mass. These tongues appeared to be essentially solid but yet showed some slight creaking advance.

On the evening of March 6 occurred a most spectacular outbreak of lava fountains on Mesa de Los Hornitos, above the buried Taquí lava vents. Dr. Frederick H. Pough has given us an account of this event:

Te Ata, Luis and I went around to the far side of the volcano [west] to photograph the blue flames at close range. We crossed the older lava dotted with hornitos and came close to the foot of the cone. At this spot a ridge 100 feet high and with two humps each about 30 feet high extended toward the west. A saddle about 5 feet lower separated them, and a second saddle, about 10 feet lower, joined the first hump with the main cone. The flow to the southwest was very jagged and since it was still hot was impossible to cross, so that the cone could be circled only along its base. Coming to the ridge we attempted to cross at the lowest saddle where it met the cone, but found that we could not do so because of a fumarole emitting hot, acrid gas with considerable force. We crossed above it by climbing up the slope of the main cone.

Beyond the ridge were several hornitos and volcancitos. An isolated peak, about 25 feet high, showed a cascade of frozen black lava extending from its throat to its base. At the north side of a second hump there was a beehive volcancito with a similar but less well-formed lava cascade. Gas was being forcefully emitted by both these vents.

That evening we found the volcano in only moderate activity with an occasional small bomb rolling down the slope. Since it was still light we dawdled around the base of the cone until it began to get dark. No particular or unusual activity was seen in any of the volcancitos, nothing to attract any special attention.

Shortly before seven, as it began to darken, it was decided that we might as well get to our station and prepare to photograph while we could see. Luis, carrying the tripod, led the group and as he surmounted the ridge he saw that the volcancito we had selected for the photographs had become very active and was emitting lava. A pool of lava had filled the throat and was beginning to overflow to the northeast. Gas was still coming out with force, making huge bursting bubbles, splashing fragments several feet in the air. The lava was not very fluid, and though the slope was considerable and the temperature high, as indicated by its orange color, it flowed with some deliberation.

The noise that accompanied this eruption was much like that of the plopping of a mud volcano, plus a hissing of the escaping gas. While we were watching this spectacular display we noted an increase in activity in the isolated volcancito behind us, which began to throw out a few gobs of molten matter.

The activity from the first vent continued, with occasional bursts from the nearer vent, but most of the eruption was concealed behind the ridge. It was not possible or safe to go onto the recent flow, so the only alternative seemed to be to climb on the main cone. As we started our climb we noted that minor activity was showing in several other vents, all throwing out rocks and casting a glow on the escaping vapors suggesting that incandescent lava was in the throats, and that the gas output had increased. The plan of going along the slope was revised when the small fumarole in the saddle began to throw out a few rocks. In a few minutes this vent became increasingly violent and soon lava welled up in its throat and began to spill over. Meanwhile the whole series of volcancitos which made up the complex of the ridge was repeating this overture, with lava spilling from several of them. In about ten minutes—it was now completely dark—a thrilling spectacle developed. The lava seemed to enlarge the vents and to expand into considerable-sized openings. Gas rushed out and breaking bubbles threw liquid fragments high in the air, probably 150 to 200 feet. The solid fountains of the lava were about 20 to 30 feet high, and above them the air was filled with flying fragments. The fountains cascaded down to form a flow, not very fluid but advancing in big ropy curds in a stream about two feet thick, ferrying cooler bits on its surface. Activity kept increasing and, although we were standing about 100 feet from the vent, the lava fragments soon began falling unpleasantly close. We decided then upon another retreat; salvaged our instruments from where they had been placed only a few feet in front of the advancing tongue and went further back on the old flow.

From this spot about 100 yards from the vents we had a magnificent view of seven simultaneously operating lava fountains, with the flowing lava merged into a single front advancing toward us over the older partially ash-coated lava. The sounds were still the same, the noises of a dozen mud volcanoes, with a plopping and a hissing and a little crackling from the cooling lava surfaces all merging into one amazing concert. Not all of the gas vents were producing lava. In some places holes were blown in the flowing lava by gas vents which were being covered as the liquid advanced. They looked dark, but were probably dark in the sense that sunspots look dark on the disc of the sun.

Gradually the eruption began to die down, the fountains diminished, and the fragments were no longer tossed so high in the sky. By 8:00 all but the vent in the saddle had ceased producing fountains. The whole spectacle lasted little more than an hour.

On March 21 the area about the Taquí vents, now called Mesa de Los Hornitos, showed still further changes. Most conspicuous changes were in the volcancitos. The largest volcancito, which presented a wide open mouth on its south flank, was now a symmetrical cone about 15 meters high, with a deep chimneylike opening at its summit. From its summit vent arose pale-bluish fumes, and its throat was oxidized to a brick red bordered by yellow incrustations. The north side of the volcancito was tinged and colored with yellow salts. The neighboring volcancito, from which previously the biggest flames arose, was collapsed on its south slope. The orifice of its vent was likewise oxidized and altered, and faint-bluish fumes arose from it. The cavelike orifice was now less active than previously; and a small congealed lava flow, apparently from one of its own vents, covered the floor. It was now evident that this cavelike apparatus was a collapsed volcancito. On the floor of this old volcancito, a tall, slender hornito had formed rising slightly above the old rim. This hornito, which we called the Soplete, or blowtorch, because of its action, could be observed readily from a distance of a few feet from a station on the old volcancito rim. From its summit orifice, gases rushed with a hissing. Stones tossed into this orifice were immediately ejected by the rush of gasses. At night one could see a blowtorchlike flame of pale blue issue from its summit vent (pl. 37*A*). Sticks held in this flame were readily ignited. We succeeded in breaking off the tip of the Soplete and found it lined with brilliant spangles of hematite and delicate arborescent groups of magnetite.

Immediately west of the "cave" was a new feature, a "window" in the congealed crust where the flowing lava could be observed. David Gallagher [23] had already observed this window on March 8. The window was about 3 meters wide, 12 meters long, and bordered at its head and lateral sides by a levee of scoriaceous lava, presumably built up by spatter from the flowing lava stream. The lava issued quietly from beneath the crust and flowed calmly, except for a low heaving motion, to disappear again beneath the crust at the lower end of the window. Its rate of flow was estimated at about 1 meter in 5 seconds. Bluish vapors with a strong acid odor arose copiously from the flow.

A considerable area north of the volcancitos was covered by a fresh flow of pahoehoe lava (pl. 36*A*), a lava form rarely observed at Parícutin. Ropy structure was not well shown; instead, the lava showed a flat, hummocky surface with a slaggy skin covered with fernlike streaks of stretched vesicles. The source of this pahoehoe lava could not be exactly determined but appeared to be the large cone-shaped volcancito.

[23] Personal communication.

An unusual type of lava also observed at this time consisted of elongated ropy blocks, heaped together like logs of cordwood in a jumbled pile. The lava appeared to be closely associated with the pahoehoe flow.

During the night of March 21–22, the lava in the window ceased flowing and congealed, and the lava wall about the window collapsed. The large conical volcancito had also collapsed, yielding a depression about 20 meters long and 10 meters wide surrounded by the low domelike remnant of the original structure. The bottom of this depression was now covered with congealed lava, except at each end, where shafts with incandescent throats were located; each yielded bluish-white fumes. The Soplete and other hornitos between the volcancito and the window had also ceased their activity. This sudden cessation in activity suggests that lava had ceased flowing from the vent beneath the lava crust or that the flow was diverted into another channel.

TREMOR ZONE

Shortly after the outbreak of the Taquí vent, the Tarascans moved their refreshment stands from Cerro de Jarátiro to a broad terrace at the foot of Cocjarao Mesa, directly opposite Mesa de Los Hornitos, for the spectacle for tourists was now the ever-changing lava activity of the Taquí vents. This campsite became known as Campamento de Aurora. A few hundred meters to the south was the zone of fissures mentioned in the section entitled "Taquí vents." On March 22 we discovered quite by accident that this belt was also a "tremor zone." It was noticed that in the belt of the old fissure zone, the ground was in a state of varying but continuous trepidation which, however, was not perceptible 100 meters to one side or the other. The zone could be delimited by sitting at various points in the area or, as we found later, more easily by observing the tremor of the branches of the dead pine trees. A plumb bob suspended from a log partially buried in the ash clearly demonstrated the variations in the trepidations. This zone of tremors had a direction, as near as could be determined, of N. 60° E. (magnetic) and coincided, as nearly as our information allowed, with the direction of the original fissure of February 20, 1943. The line of the volcancitos had a direction of N. 65° E. (magnetic). We have no evidence, however, that this apparent coincidence had any real significance.

A striking relationship between the variation in the intensity of the tremor and the explosive activity in the main crater was readily apparent. Although in general the trepidations were gentle and only apparent when one was seated somewhere along the zone, there were frequent intervals when the tremors suddenly increased and were relatively strong for an interval of less than a second. Three and a half to four seconds after these sharper shocks, an eruptive burst occurred in the crater. The estimated distance from Campamento de Aurora to the crater vent was about 1,000 meters. It was repeatedly noted after an unusual lapse of time without explosions that the next tremor would be relatively strong. One month later, on May 22, the tremor zone showed weaker but still distinct trepidations.

CRATER ACTIVITY

During March the eruptive activity in the crater was quite variable, ranging from a weak eruptive column with a deep rumbling to huge wooly cauliflowers rising in continuous succession but with little sound (pl 38*A*, *B*; 39*A*). The active vent appeared to be very close to the southwest crater rim, which was lower than the north rim, presumably owing to the proximity of the eruptive throat.

On March 21 at 4:10 p. m. a strong earthquake shook the area. Immediately preceding the shock, the crater showed only mild activity. Directly after the shock, activity increased greatly; and large cauliflowers of pale gray developed rapidly but silently, or with little noise. Although the eruptive activity for the last several days was similarly variable and because the previous earthquakes induced no apparent change in the eruptive activity of the crater, it is more than likely that this apparent effect was purely fortuitous. There was also no apparent change in the activity of the volcancitos or hornitos.

During these days few bombs fell on the cone. The ash consisted largely of porous concretionlike masses, frequently elongated to resemble fragments of twigs. Some shredded ash, of the Sapichu type, also fell, particularly when the eruptive column was tenuous and the noise a deep-throated rumble.

During the night of March 25 the activity in the crater increased to violent proportions. About midnight a tremendous explosion showered Campamento de Aurora with huge bombs, causing the Tarascans to flee their posts in precipitous haste to Mesa de Cocjarao. Fortunately the bombs were channeled into a narrow zone immediately north of the camp, but they fell there in such abundance that hardly a square meter did not contain a large bomb, and they shattered every tree in the area. Numerous bombs were found a mile from the crater; and later we found one, more than a meter in diameter, nested in its crater in the ash on the summit of Mesa de Cocjarao. With this great explosive burst, the activity subsided. One effect of these heavy explosions during the night was to lower markedly the southwest rim of the crater.

The activity of the volcano continued with little appreciable change, except perhaps for a diminution of ash in the eruptive column. From this period on, the majestically rising eruptive column was frequently very pale, or even pure white, indicating a minimum amount of included ash. Sometimes the column rose, without visible vapors, as a tenuous cloud of pale-brown ash, accompanied by a deep, throaty rumble (pl. 39*B*). A pale-brown shredded ash, like that of Sapichu, fell sparingly during such an eruption. This suggests that the eruptive throat was open and not choked and that the rushing vapors abraded the open throat of its fused lining. At night when many bombs were being hurled out of the crater, the effect was particularly beautiful; for the incandescent rocks stood out clearly against the deep-blue backdrop of the sky unobscured by the rising vapors or falling ash, and a glowing reflection tinted the clouds above a deep, rich rose. Alternating with these periods of white eruptive column or tenuous ash were times when the column rose in its normal manner, ascending in voluting cauliflowers of dark gray.

On April 4 at 11 o'clock a strong earthquake was felt in the area.

LUMINOUS PHENOMENA

An unusual phenomenon observed on the night of April 5 should perhaps be reported here, although it admits of no ready explanation. While we were approaching our camp on Cerro de Jarátiro, on horse by trail from San Juan Parangaricutiro accompanied by several Tarascan horsemen, Foshag, who was well in the lead, saw what appeared to be a vivid flash of bluish light about the base of the cone. The base of the cone itself was screened from the view of the other members of the party by the ridge upon which the camp was located, but a few minutes later another flash appeared and was seen by other members of the party and caused one of the Tarascan horsemen, who had in the meantime advanced toward the head of the caravan, to cry, "Rayos por abajo!" [Lightning from below.] Observers at the camp reported having seen nothing, which led us to believe that the brilliant flashes were no more than an illusion.

On April 24 we observed another and definite curious luminescent phenomenon above the cone. This luminescence was first called to our attention by Ing. Ordóñez, who had seen it strikingly displayed the previous night and described it as "searchlights playing out of the crater." It appears that this unusual occurrence owed its origin, or at least its visibility, to a special disposition of centers of activity in the crater. A thin erect eruptive column rose continuously and without apparent force from a vent very close to the northeast edge of the crater. The night was still, without wind, but the upper currents of air carried the eruptive column lazily toward the east, revealing sparkling stars in the clear, cloudless sky in the area above the crater. A second vent near the center of the crater gave off single lazy bursts at intervals of one-half to an hour or more. The dust of the explosions from this second vent drifted slowly toward the west, in the direction of Cerro de Canicjuata. In the region where this dust cloud eventually disappeared, a dancing luminescence appeared, usually at a height estimated at 200–1,000 meters above the crater and extending well over toward Cerro de Canicjuata. This luminescence differed from the ordinary pink reflection of incandescent lava upon clouds or rising vapor by its bluish-white color, and in the fact that it persisted long after the ash cloud had dissipated entirely from view, and the stars were distinctly visible through it. Its appearances reminded one, in its movement and color, of the aurora borealis. It appeared most distinctly some time after an eruptive burst from the central vent and remained clearly visible until the next explosion occurred, alternately expanding toward Cerro de Canicjuata and then retracting toward the crater. We watched this spectacle for several hours, seeking some simple explanation for it. Less striking, but still well defined, was a shaft of light of similar appearance that followed the inner, or crater, side of the eruptive column. From Ordóñez' description, it appears that the phenomenon showed itself even more strikingly the preceding evening.

THE CRATER

After the long period in which the crater showed persistent explosive activity, the volcano became somewhat more erratic in its action, and there were brief periods of consistently reduced activity when it was feasible to climb the cone to the crater rim. On May 22 activity in the crater was still normal; a full eruptive column rose majestically in full voluting cauliflowers, apparently from a centrally situated vent. But on the 23d, activity was reduced to a lazy, weak column, charged with a pale shredded ash, which on the 24th was still further reduced to a tenuous dust column with little visible vapor. On May 25 visible emissions had almost ceased, although a deep, low growl from the crater indicated that gaseous emissions were still being given off. Advantage was taken of this condition to make our first ascent of the cone and to perceive its shape and observe the character of its activity.

The crater was eccentrically funnel shaped, the southwest wall being steeper than the other slopes and the southwest rim lower. The western slope showed a narrow bench from the crater rim to a precipitous slope of semiconsolidated tuff, the bench being the remnant of an older inner slope when the crater floor was at a higher level. Except for the gentle slope from the rim to this residual bench, the crater rim was very sharp. The inner slope of the crater, made up of loose or only slightly consolidated lapilli, with very few bombs, sloped directly to a small basin appearing to be no more than 2 or 3 meters in diameter (pl. 40*A*). At times this basin showed incandescent lava and even produced a few weak gas bubbles that spattered some lava a few feet into the air. Usually, however, the basin floor was covered with ash that slid down from the nearby slopes. Occasionally this vent showed some mild and sporadic activity, during which a brownish dust arose in a thin, weak, and tenuous column. Somewhat higher than this lower vent was a circularly depressed area in the side wall of the crater. This saucer-shaped depression was about 8 meters in diameter and bounded by an almost continuous circular crack. In the bottom of this saucer were two small irregular vents, and around them was a halolike zone of thin sublimate products. Steam issued from these two vents almost continuously with a tremendous grating roar. For much of the time, the vapors issuing from the vents were invisible, their presence attested only by the deep roar from the orifices and the condensation of the vapors into irregular rising clouds above the crater rim. At other times, however, the vapors rushed out of the vents as visible jets of steam, as if escaping from a nozzle at high velocities. No distinct odor was apparent on the crater rim. Except for the emission of vapors, which condensed in tatters of clouds above the crater rim, there was little else given off by the crater vents, and the crater activity can be said to have been in a greatly reduced state.

During this rather erratic and reduced state of activity, there appeared little movement of lava in the flows. Issuing from a secondary vent in the Taquí lava front, a subsidiary tongue of torn and twisted lava was advancing slowly over a portion of the lands of La Lagunita. Activity at the hornitos, however, indicated that the lava still flowed beneath the congealed crust at Mesa de Los Hornitos.

HORNITOS AND VOLCANCITOS

Late in the afternoon of May 24, several interesting events took place which throw some light on the formation of hornitos and volcancitos. At the "cave"—a collapsed volcancito that was a prominent feature of Mesa de Los Hornitos for the last few months—a small lava flow suddenly broke out, issuing from a small area of jumbled rock, locus of the original volcancito vent. This pasty lava flowed slowly from the vent, and the throat soon became a bubbling mass of viscous lava from which doughy bombs were thrown out to the height of a few feet. These masses congealed to irregular shining black masses. Two narrow open fissures in the congealed crust of the lava of Mesa de Los Hornitos connected the cave with a large asperous hornito that occupied the former site of the lava window. These crevasses were lined with a thin film of sublimates, fine spangles of hematite, and a chocolate-colored dust. From a point on the larger fissure, there suddenly issued a rush of gas with a loud hissing and a small column of fine brown dust, followed by a very vesicular froth of viscous lava that grew within a space of a quarter of an hour into an hornito about a meter high. The rapid rush of gases from the orifices blew small irregular fragments from the vents and even loosened larger slaggy masses from the growing hornito. In this manner a hornito originates and grows—a froth of gas-laden lava spewing from a crevice upon the crust of the flow. We were unable, unfortunately, to continue our observations on this hornito during its complete life.

At the same time, a large conical volcancito, lying between the cave and the base of the cone, began to pour out a thin viscous tongue of lava from its summit orifice which, flowing down the steep side of the cone to its base, congealed as a small rough flow, demonstrating the manner in which a volcancito grows in size.

PARANGARICUTIRO LAVA TONGUE

From its outbreak on January 8 along the south and east base of the cone until early April, the Taquí lava flow had advanced to the east base of Cerro de Equijuata, filling the valley of Tipacuaro from Cerro de Equijuata on the west to Lomas de Capânguito on the east. Its advance had now practically ceased, only a few weak lobes moving slowly and erratically forward. By April 24, however, lava burst out of the summit of the Taquí flow and covered the lands of Turímbiro near the east base of Cerro de Equijuata and reached the San Juan Parangaricutiro–Uruapan road, advancing in two tongues and threatening the waterline to the town. Its front was now but 0.6 kilometer from the outskirts of the town. A lava stream about 10 meters wide flowed quietly from its vent at a rate of about 180 meters an hour.

The east approach to San Juan Parangaricutiro was through the short narrow valley of Juanantacua, connecting the arable fields of Rancho Tipacuaro with the town. To the south of this valley rose the steep wooded slopes of Cerro de Capatzun; and to the north, the slopes of the mesalike fields and woods of Nicorroso that lie between San Juan Parangaricutiro and Angahuan. Through this narrow valley passed the road from Uruapan to San Juan Parangaricutiro. During the month of May, the lava flows which broke out of the lava front at Turímbiro and were actively advancing in April completely filled this small valley and came to rest in the cemetery at the edge of the town. The main lava front extending across the valley for a distance of 150 meters was about 10 meters high and had the usual appearance of a mass of block lava, rubble, and clinkers. At this time we were not impressed with any essential difference between this flow front and others we had witnessed, but photographs suggest that this form was more clinkery and less blocky than previous flows. A narrow tongue of torn and twisted lava had advanced several hundred meters down the narrow but steep-walled Arroyo Principal, which passed the eastern edge of town. Such torn and twisted lava, although observed previously as short ephemeral lobes in the earlier flows, was, as we shall later see, the characteristic lava of the late stage of the Taquí flow.

After a period of repose the lava front, at the edge of the town of San Juan Parangaricutiro, again resumed its advance and on June 17 began to invade the town itself (pl. 40*B*). The flow followed Arroyo Principal at the eastern edge of the town but, spreading laterally when the arroyo was filled, soon reached the first street. The new advance of lava showed distinct differences both in character of movement and in structure from previous flows. The advance of the lava down Arroyo Principal was rather rapid; the lateral spread was at a rate of 1 to 2 meters per hour. But instead of advancing as a moving front of rubble, the lava moved as distinct and independent lobes. At intervals along and usually halfway up the lava face, viscous lava broke out in tongues. The movement of the lobes persisted for less than a day, when they congealed; and the intervening sectors put out other lobes. These lobes sometimes issued from distinct orifices, yielding rough tongues suggesting tooth paste squeezed from a tube.

At the same time, the main body of lava continued its advance, yielding not so much the clinkery blocky surface of the earlier flows but huge torn and slaggy masses (pl. 44*B*). Torn and striated blocks rose above the general level of the lava, frequently showing a grooved, or harsh surface. The creaking of the moving blocks was frequently heard. The lower portion of the Taquí flow, beginning at the cemetery and extending to its ultimate advance at Huirambosta, we have called the Parangaricutiro tongue.

The advancing tongue, as it flowed down the steep and narrow Arroyo Principal, frequently showed remarkable fluidity. At a point about a kilometer below the town, the flow advanced down the arroyo as a steep front at a rate of about 40 meters per hour. Almost the entire front, confined by the steep high walls of the arroyo, was incandescent and flowed like soft tar in bulging lobes. This rapid and incandescent advance compared in rate of movement and apparent liquidity to other lava flows near their source. If one considers that this lava had presumably left the Taquí vent 6 months before and had already traveled 8 kilometers, with several pauses, the retention of its heat and power to advance seems remarkable. A few days later a number of distinct lava streams broke forth from the summit of the lava flow near its farthest advance and, moving rapidly down the flanks in radial incandescent streams, spread out into a fan-shaped mass (pl. 44*A*), covering 350,000 square meters of terrain in a single night.

During this period (June and July) the rainy season was already well advanced, and the high humidity of the atmosphere was conducive to the condensation of vapors emitted by the lava, so that these vapors frequently became distinctly visible, particularly over the lava at the cemetery where it had accumulated in considerable thickness in the narrow stretch between Cerro de Capatzun and Cerro de Calvario. Banks or clouds of vapor formed several hundred meters above the lava flow, with moving pendulous stringers, or "tails," of vapor hanging below them and indicating that the lava, although now more than 6 kilometers from its vent, still contained and emitted considerable vapors.

Eruptive activity in the crater during the summer was considerably reduced and more erratic than previously (pl. 42*A*). Frequently the pure-white eruptive column contained only ashless vapors that rose languidly, sometimes to a great height. At other times invisible vapors issued from the crater and condensed as white cumulus clouds above the volcano. It was often difficult to distinguish these eruptive vapors from the normal clouds brought on by the rainy season. At other times the column consisted of a tenuous brownish dust without visible vapors.

DESTRUCTION OF SAN JUAN PARANGARICUTIRO

The steady and inexorable advance of the lava finally convinced the remaining inhabitants of San Juan Parangaricutiro that they must evacuate their town (pl. 41*A*). Previously many people, mostly Mexicans, took advantage of their government's offer to resettle on new lands near Ario de Rosales in Michoacán. The remaining population, chiefly Tarascan, elected to remain, hoping that some miracle would occur to save their homes. Now, as the lava covered plot after plot and destroyed each street in succession, they made feverish efforts to salvage their possessions and the lumber of their houses. The sacred Señor de Los Milagros was moved in solemn procession to Uruapan, and the interior of the church was dismantled. Because of their deep attachment to the soil, many remained until the lava covered the last small corner of their land, then sadly departed by the trucks their government had placed at their disposal. With the destruction of the church the strongest tie that bound them to the place was broken. By mid-July all but a few outlying squares at the western edge of the town were covered by lava. Of the church only the 75-foot towers projected above the torn lava surface (pl. 43*A*), and the apse with its altar nestled within a basin of jumbled lava blocks. Curiously enough, a small kipuka [24] within the middle of the flow lay uncovered a short distance to the northeast of the church.

The following described July days may be considered as typical of the events during this period:

July 6, 1944.—As we entered San Juan Parangaricutiro at about 7 p. m., the cone showed two well-defined and separate eruptive columns: one from the central portion of the crater rather weak and very pale gray; and one from the south vent, more voluminous and grayer—both rose rather languidly without cauliflowers. No noise was audible in San Juan Parangaricutiro, and there were no incandescent ejecta until about midnight when bursts of glowing ash appeared intermittently in a column of increased size and a few bombs fell on the west slope of the cone.

We found that the lava had spread considerably toward the west, across the northern part of the town and less toward the southwest in the direction of the church, from which it was now only 25 meters distant. As before, the lava advanced as spreading tongues, or lobes, moving toward the west at a rate of about 2 meters per hour and toward the south about 1 meter per hour. The north and faster-moving lava front was lower (3 meters high) than the south slower front (5–8 meters high).

During the night the eruptive column rose majestically to a height of 1½ kilometers and was then carried abruptly toward the southwest by the upper air currents.

July 7, 1944.—During the morning, a weak column of gritty somewhat brownish ash rose without great force or cauliflowers or perceptible vapors. Sometimes two types of eruptive columns could be distinguished simultaneously, weak and pale from the central orifice and larger, denser, and darker from the south vent, both columns erratically increasing or decreasing.

We talked with a man from Los Reyes about 30 kilometers west of the volcano who reported that the heavy rains were carrying great quantities of ash down the streams, burying fields and filling irrigation ditches, and that last year the ash did great damage to the sugar cane.

The lava continued its normal advance. The people of the town busily removed the last of the houses and dismantled the interior of the church. The men removed the heavy beams, while the women and children carried away the cupboard doors and the flower stands. On this day they removed the pulpit, confessional booths, and the carved stone baptismal font. The padre believed that the church would have remained secure, had they not removed the sacred image of the Senor de Los Milagros. Only a few old people remained, and

[24] An uncovered open space, surrounded by lava (Stearns and MacDonald, 1942).

338669 O—55——8

they feversihly dismantled their houses by day and disconsolately watched the advance of the lava by night—there remained but one street free of lava in the town.

We made a tour of the lava front in the late afternoon and evening. The west, or lateral, lobe had decreased its rate of advance; and behind the church it no longer showed apparent motion, having stopped 20 meters from the apse; but a new tongue was advancing from the northeast toward the parish wing. The flow down Arroyo Principal showed renewed activity after a period of almost complete quiescence; tongues of viscous lava broke out laterally at many points. At Hidalgo Street three caves with domed roofs had formed in the lava, presumbably by the arching of the surface crusts. The main flow had increased in height to about 15 meters above the ground level, making its total thickness from the arroyo bottom about 20 meters. Some lateral tongues broke out near the crest of the main flow and flowed viscously down the lava front. We watched a fine lateral tongue issue from a cavelike orifice near the crest of the main stream, flowing like soft tar down the torn and jumbled lava face and finally spreading fanwise at the base of the flow. Near the terminus of the main lava tongue a number of flows broke out from the top of the lava and moved in radial streams from their source (pl. 44*A*). The main lava flow at this time was 1⅓ kilometers beyond the outskirts of the town.

Little incandescent ejecta came from the crater at night, and a few bombs fell on the south slope of the cone.

Very heavy rain in midafternoon obscured the cone, and after the rain much water vapor arose from the Parícutin flow of June 1943.

July 8, 1944.—The lava tongue behind the church showed no apparent movement, but the new lobe advancing from the northeast approached slowly and was only 20 meters from the parish wing of the church.

We went to Zirosto village, 8 kilometers west of San Juan Parangaricutiro, following the length of the flow. The lava tongue had now reached the Llano de Huirambosta, almost 2 kilometers beyond San Juan Parangaricutiro. The activity of the lateral tongues, so strikingly active last night, had now diminished or completely ceased. The summit flows of last night had spread fanwise over the fields to cover a large area of land but were now completely motionless.

The forest along the Zirosto road was badly damaged, with broken limbs and many dead trees. The fields of Zirosto were covered with a heavy mantle of ash, for the heaviest falls of last year drifted largely in this direction. About one-half of the inhabitants had deserted the town. One of the inhabitants reported the depth of the ash to be about a meter. Attempts to raise corn in the ash failed; for although the seeds sprouted, the shoots soon withered and died.

Action from the crater remained erratic and apparently continued from two vents, with billowing cauliflowers from the central orifice, and a gritty column from the south vent. Frequently the white vaporous eruptive column was completely lost, commingling with the clouds drifting in from the west.

There was very heavy rain during early afternoon. Some of the waters of Arroyo de Nureto (near Angahuan) were collected and the volume of volcanic ash was found to be more than half.

By early August the lava tongue of San Juan Parangaricutiro had entirely ceased its movement, its ultimate advance reaching Llano de Huirambosta, where the arroyos of Parícutin and San Juan Parangaricutiro joined. The Taquí flow, following its mean course, had a length of 10 kilometers with a maximum spread, over the lands of Quitzocho, La Lagunita, and Huaririo, of 2½ kilometers.

LATER STAGE OF TAQUÍ FLOW

The Taquí vent continued to yield abundant lava, which sometime during late July or early August, instead of finding its way by subsurface flow to the lava tongue of Parangaricutiro, advanced as a sheet from an undetermined point overriding the previous flows around the base of the cone. This secondary vent fed a front of lava that spread from the cone across the valley to Curínguaro, advancing as an irregular wall toward the north. A narrow tongue turned westward and passed the base of Sapichu and flowed between the old ash-covered Quitzocho flow and the flanks of Cerro de Jarátiro, its ultimate narrow and torn tip forming a sliver of lava between the Quitzocho ridge and Cerro de Jarátiro. This tongue of the Taquí flow we have called the Campamento tongue. By August 15 the Campamento tongue had built a wall of rubble rising above the level of the second Cerro de Jarátiro crater; and a thin stream of lava, flowing between low-bounding levees of rubble, reached the bottom of the old crater where it formed a low fanlike delta. On the 17th, liquid lava broke out of the front above the old Cerro de Jarátiro crater rim along a front of about 30 meters and poured into this ancient crater. Within 6 hours the flow filled the old crater almost to its lower eastern lip. The effect of this outbreak was to drain fluid lava from the main body of the Campamento tongue and to form a graben-like depression traversed by rubbly parallel ridges extending toward Sapichu. Soon after, new incandescent tongues issued from secondary vents in the neighborhood of Sapichu, which appeared, in the obscurity of the night, to come from points near the head of the subsided or grabenlike area.

It is unnecessary to report here all the vagarious movements of the lava tongues of the flow during this period. It will perhaps suffice to say that at a number of points along the slowly advancing lava front fluid lava broke out of its enveloping mantle of rubble and clinkers to send out lobes and tongues, and even flows of considerable extent (Bullard, 1947). These subsidiary flows now occurred frequently. In the previous flows these tongues were not common and were then usually only short lobelike protrusions. Their more frequent occurrence may be ascribed to the flatter terrain over which the main flows passed and their resultant slower advance, with consequently greater accumulation of fluid lava in the main body of the flow. The pressure of this "intruded" lava must then find some release through the rupture of the enveloping shell.

On September 27 (Bullard, 1947), lava from the Taquí vents, after having flowed for more than 8 months around the south and east sides of the base of the cone, began flowing toward the north, following Arroyo de Parícutin and filling the valley between the first Parícutin flow and Cerro de Canicjuata (pl. 50). This new flow issued from a "graben" in Mesa de Los Hornitos. Upon reaching the flatter terrain about Parícutin, it spread laterally and covered the site of that unfortunate ash-buried village. Continuing along Arroyo de Parícutin, it invaded Llano de Huirambosta and on October 20 finally joined the Parangaricutiro tongue near the end of its course. This later Parícutin flow showed the normal characteristics of Parícutin's lava, a high steep front, mantled with broken blocks and clinkers, and partial discoloration by gaseous emanations. The contact of these two lava flows formed an interesting contrast of lava types. A few weak fumaroles developed in the lower part of the flow but did not persist.

THE CRATER ON NOVEMBER 26, 1944

A second ascent to the crater was made on the morning of November 26. The general configuration of the crater was somewhat changed from that as we saw it on May 25. The rim of the crater was now rounded and not sharp as on the previous ascent, and one could walk along the broad crater edge with ease. The highest point on the crater rim was the eastern edge, where the aneroid read 2,740 meters. The western edge was somewhat lower, 2,710 meters and the north lip 2,690 meters. The south lip was the lowest, but a regular shower of bombs in this direction precluded a complete circuit of the cone. The inner north slope of the crater was occupied by a bomb-littered bench, the remnant of a previously higher floor. The inner edge of this bench, which rose slightly from a low trough, had an altitude of 2,675 meters. From the rim of the crater and the bench, the sides sloped down to two orifices, a central and a south vent.

The central vent was a deep, narrow funnel and showed but little activity. Small clouds of white vapors rose lazily from the orifice, occasionally increasing in volume until they filled the bottom of the crater.

The south vent was a saucer-shaped depression in the bottom of which were 5 or 6 main orifices, with perhaps some smaller ones. This vent showed violent but erratic steam activity; jets of vapor rushed from the orifices with great velocity, abrading the adjoining crater wall. The individual jets of vapor coalesced somewhat below the crater rim into a medium-sized light-colored eruptive column. Activity in the individual orifices was not steady but irregular and erratic. The largest orifice was an irregular opening, perhaps 4 meters across, which blew off at frequent intervals tearing incandescent lava from its throat and carrying bombs well above the crater rim. Orifice number 2 was small, less than a meter across, and almost continually blew off white steam. This orifice had a cone mouth, like a miniature volcano, about three-fourths of a meter high. Orifice number 3, not clearly visible, gave off copious white vapors directed toward the southwest. Orifice number 4 appeared to be a double vent that blew off at intervals of ½ to 3 minutes toward the west and carried some ash. Other vents could not be clearly distinguished in the vaporous confusion in the crater pit.

The vapor column carried with it bombs torn from the throat of the vents. One could sometimes observe a large bomb torn from the orifice. The vents also discharged finer material. In addition, the eruptive column scoured ash from the nearby wall. Occasionally material slumped from the crater walls into the vent and was blown out in ashy volutes by the rushing vapors.

The noise of the vents, particularly from orifice number 1, as heard from the crater rim, was almost deafening. Numerous shocks swayed the upper part of the cone, particularly near the lower south rim, where the tremors were so strong and frequent as to induce in one a feeling of dizziness. Frequently the activity in the orifices of the south vent increased after a heavy tremor, but no regular relationship was observed.

RAIN EROSION

During the rainy season of this year, June-September 1944, storms seemed to be more frequent and violent than during the preceding rainy season (pl. 41*B*). The ash mantle of the area surrounding the volcano showed much more erosion than previously. The steep hill slopes, like those of Cerro de Jarátiro and Cerro de Canicjuata, were deeply rilled and gullied (pl. 47*A*), extending down even to the original soil cover. The abrading action of the ash-laden waters and the disappearance of grass or herbaceous cover allowed the rapid scouring of the original soil so that denudation of the hill slopes took place at an accelerated rate. It was early noticed, however, that the ash beneath the pine trees was more resistant to removal, owing to the accumulated mat of pine needles, which served the same function as pine needles or straw in adobe. On other slopes, like that of Cerro de Canicjuata, a downhill tilt of the dead pine trees indicated a downhill creep of the ash blanket.

A single storm might excavate a deep steep-walled arroyo in the heavy ash cover. Such an arroyo, 7 meters deep, formed along the base of Cerro de Canicjuata (pl. 47*B*). The material excavated was spread at the mouth of the arroyo as a low alluvial fan extending over much of the area formerly occupied by the village of Parícutin. Boulders weighing 20 kilograms or more, found intermingled with sticks and grass in the crotches of trees, attest to the transporting power of these heavily ash-charged streamflows.

AHUÁN FLOW

Sometime in mid-November, exact date not known, lava broke out at the south base of the cone, below the south vent in the crater (pl. 45*B*). Accompanying this flow was a slump in the south slope of the cone, forming a triangular segment, reaching about one-half the way up the slope of the cone. At the eastern end of this break the crater slope showed a steep, half-funnellike slide at the base of which issued the lava stream. As near as can be judged, this point coincided with the vent (fig. 123) of the September 1943 flow and occupied a position on a line through the main crater and the Sapichu vents. A small lava dike was exposed in the wall of the cone a short distance above the lava vent. This dike, 50 centimeters wide, had a strike of N. 10° W. (magnetic) and a dip of 65° E. On the opposite side of the lava stream, or to the east, was a small pyramidal hill of fume-oxidized ash evidently a section of the main triangular slump, which was broken off, twisted, and carried about 100 meters by the outbreak of the lava. At the south base of this small hill stood a contorted slab of lava, a part of the dike exposed in the cone's wall. This slab had a remarkable resemblance to a seated rabbit, and for this reason we named the vent Ahuán [auani (Tarascan)=rabbit]. The lava issued quietly from the base of the funnel-shaped slope, passed under a low lava bridge where congealed crust had already begun to form, flowed with a faint tinkling, and emitted choking bluish fumes. The flow showed a bright-orange incandescence dappled with abundant dark scoriaceous clinkers.

On December 2 we were able to cross the rough clinkery surface to the edge of the moving lava stream. By this time the apparent vent

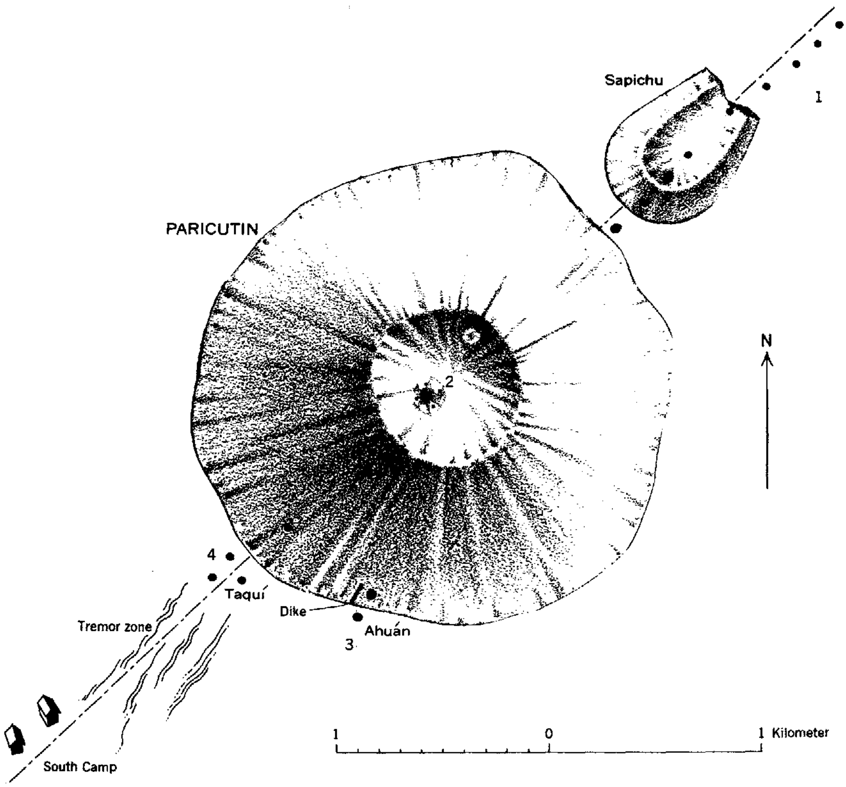


FIGURE 123.—Parícutin volcano, showing the vents of 1943-44.

1. The Sapichu vents of October 19, 1943.
2. The Cuiyúsuru or main crater vent.
3. The Ahuán vents.
4. The Taquí vents.

had moved downstream about 10 meters owing to the congelation of the surface over the upper part of the flow. At the head of the flow was a low horseshoe-shaped levee about 2 meters across. Between this levee and the moving lava were several incandescent crevasses from which hissing invisible vapors issued. Lava issued quitely from the narrow vent. About 50 meters below the vent the stream was 6 meters wide. It showed an orange incandescence dappled black by congealed lava and did not break up into clinkers in the upper part of the flow. The flow moved quietly with an occasional heaving of the surface. On rare occasions these heaving spots swelled to large blisters, some of which burst with a hiss and scattered incandescent masses of viscous lava. This flow we have called the Ahuán flow.

Roughly paralleling the lava stream were irregular low ridges of clinkers, apparently old levees formed on preceding days when the lava had flowed by a somewhat different course. Levees also formed along the lower stretches of the flow (p. 46*B*). About 5 meters from the stream's edge were irregular vents of escaping gases or incipient fumaroles, surrounded by a tenuous deposit of yellowish sublimates By the next day (December 3) the head of the flow had frozen over for a distance of about 75 meters, and the surface was covered with a pinnacly crust, stained with yellow and orange salts.

On the crusted head of the flow between the apparent lava vent and the base of the cone, a hornito, about 1½ meters through the base and 1½ meters high, had formed. It contained many incandescent orifices, particularly on its summit. These vents carried delicate growths of hematite and magnetite crystals. Gases issued from these vents with a continuous hissing. The maximum temperature measured in the incandescent orifices of this hornito was 1080° C (Ziess, 1946). Measurements in the crevasses surrounding the head of the lava flow were 1020° C.

By December 2 the Ahuán flow had encircled the south and east sides of the base of the cone and moved over the older ash-covered Sapichu and the Taquí flows (p.l 46*A*), the lava front extending from Sapichu southeastward across the older lava fields. The lava front reached a height of 15 meters; and from this front of rubble, tongues of rough lava extended at intervals in advance of the main flow. The subsidiary tongues sometimes reached a length of 300 meters. The whole front advanced slowly and erratically except at its northwest corner near Sapichu, where the lava front was broken by subsidiary lava tongues. One such tongue began on December 5; moved into the basin formed by the Campamento tongue of the Taquí flow, the Quitzocho ridge, and the base of the cone; and soon filled the whole basin. On December 6 lava continued to flow into this basin, moving over portions of the deeply covered Quitzocho and Sapichu flows; but since the containing slopes of the cone, the Quitzocho ridge, and the south flank of the Campamento tongue allowed little lateral expansion, the increment of the new lava raised the general level of this new tongue, creakingly lifting the already congealed surface and causing fissuring in the enclosing shell of solidified lava. At the same time, the augmented volume of new lava increased its pressure on the containing wall of the apparently congealed and partly ash-covered Campamento tongue to the extent that cracks also began to appear on the surface of this lava.

On December 7 the volume of the new lava moving into the basin continued to increase, and the fissuring in the old Campamento tongue became more evident. In the morning a small tongue of incandescent lava broke out of the Campamento flow, indicating a drainage of lava from beneath an enveloping crust. By afternoon the whole western portion of the old Campamento tongue was slowly rising, and its north face, opposite the pushing mass of the new lava, rose and steepened until it was about 10 meters high. This readjustment took place with the slow continuous fracturing of the solidified lava, and the irregular front with flow crevasses changed to a steep wall of broken angular blocks. From all directions on the flow the continuous noise of fracturing and movement could be heard. Liquid lava began to seep through the broken front. These lava seepages frequently began as an incandescent spot in the brecciated lava wall and ended when viscous lava bulged from between the rocks and flowed as a slowly moving lobe, carrying with it freshly broken blocks of the lava shell. One flow came from a newly formed narrow gash in the old lava, about 1 meter wide and 4 meters deep. This cut gradually widened until its walls were 3 meters apart. Meanwhile the viscous lava, moving down this gash, spread as a fan at the foot of the Campamento flow, but after a few hours of activity it ceased to flow.

Late in the evening a strong steady glow over the western portion of the old and apparently congealed Campamento tongue suggested the reappearance of incandescent lava. A wide and deep gash had developed and cut diagonally across the lava, almost to the pushing Ahuán lava, a distance of about 150 or 200 meters. Apparently this new channel had opened very recently, for lava had only now begun to pour from the mouth of the gash. No unusual disturbance was noted to indicate that the splitting of the Campamento tongue was other than gentle and gradual. A stream of viscous incandescent lava about 10 meters wide poured from this channel at a rate of about 10 meters per minute and began to spread out as a flat lava cake in the small basin lying between the Quitzocho ridge and Cerro de Jarátiro. This small flow spread like many of the smaller rapidly moving lobes, first by bulging forward in incandescent orange lobes, then platy slabs of congealed lava formed at the surface of the flowing lobes. As the front advanced, the congealed lava from the top slowly rotated toward the front, like the advancing treads of a caterpillar tractor, then rolled under at the foot of the flow. At a later stage loose clinker blocks formed on the surface of the flow, and eventually the whole front was a mass of advancing rubble. This small flow showed little fumes and had no decided odor.

This curious action of the apparently congealed Campamento tongue suggests that the flow contained a still fluid core, surrounded by a shell of congealed lava, and that the pressure exerted upon this body of still molten material by the push of the Ahuán lava caused the rupture of the shell and the escape of the contained molten material.

In the meanwhile new tongues of lava, breaking out from the Ahuán lava front near Sapichu, moved rapidly but erratically northward and on December 8 reached the camp and threatened to destroy the cabins. These cabins, built along the edge of one of the old craters, were about 50 meters above Quitzocho, or the fields at the foot of Cerro de Jarátiro. The great change in the topographic appearance of the vicinity can well be imagined, for it was no longer necessary to descend a high hill to reach the lava level; a glance from the cabin window revealed a high and rubbly lava front overlooking the cabin itself. A long rapidly advancing tongue moved past the doorway and spilled into the remaining uncovered portion of the parcel of La Lagunita and spreading rapidly the next day poured into the deepest and last remaining old crater of Cerro de Jarátiro.

The cabin was hurriedly dismantled and moved to the highest point of Cerro de Jarátiro, about 100 meters above Quitzocho; it seemingly was inconceivable that the lava would ever reach this elevation on the summit of a high ridge, but the cabin was again moved in December 1946 to escape a higher lava flow.

With the outbreak of the Ahuán vent, activity at Mesa de Los Hornitos greatly subsided, owing probably to a diminution, if not entire cessation, of lava from the now deeply buried Taquí vent. Mesa de Los Hornitos was greatly disturbed and traversed by deep crevasses. An ash mantle covered the lava and smoothed the asperities of its surface. The volcancitos were so modified that they were no longer recognizable, while the hornitos were mere hummocks of ash, from the summits of which protruded slaggy lava, frequently tinted by sublimates of alteration products.

Some of the crevasses in the lava crust were the reopenings of older cracks and frequently showed bright alteration colors, owing to the passage of gases through these older crevices. Some of the crevasses, too, reopened old cracks along which the froth of the hornitos had passed and exposed their channelways to view. The features of the hornitos thus exposed confirmed the previous observation that they are a froth of gas-charged lava that arose along cracks in the congealed crust of the flow. Dissection of some recently extinct hornitos showed them to have a spongy open structure. Sometimes small quantities of steam still issued from these dissected hornitos, and there was frequently detectable a sharp odor suggesting hydrochloric and sulfurous acids. The condensed steam wet the surface of the cracks and cavities and had a biting acid taste. The cavity walls of the hornitos showed considerable rock alteration. Flesh-pink to minium-red or pale-gray coatings colored the surfaces, and there were frequently nests of needle-like sulfur crystals, golden-yellow stalactites of chloraluminite, small pearly lathes of gypsum, and other less well defined products.

During the period of early Ahuán activity, the crater showed a more than usual heavy eruptive column, although only lightly charged with ash. The activity, however, was extremely variable, changing from periods of no visible vaporous emissions to heavy wooly cauliflowers with frequent lightning. From the configuration of the crater as seen on November 26 and the level of the lava vent of the Ahuán flow, it was quite evident that the throat of the crater vent and the origin of the eruptive column were not more than a few meters above the top of the rising lava column in the lava conduit.

A description of a few days in December will give an adequate idea of the character of the eruptive activity from the crater during this period of Ahuán activity.

December 3, 1944.—During the early morning hours, from about midnight until 4 a. m., the crater was very quiet, with no visible vapor column and only occasional weak bomb bursts, contrasting strongly with the heavy billowing column of last night. At 4 a. m. increased activity took place until 6 a. m., dying suddenly and leaving the cone clear except for a few small lazily rising white vapor clouds. At 9 a. m. eruptive activity began gradually to increase, soon yielding a gray wooly column of rising cauliflowers with strong erratic bomb bursts. At noon a wooly gray column arose rather lazily, accompanied by a low sound like surf. In the afternoon a gray wooly eruptive column slowly ascended with rather numerous bombs.

From 6 to 9 p. m. a heavy ash column was thrown up with intermittent bursts of bombs and brilliant lightning flashes, some vertical, some horizontal, and others irregular. From 9 p. m. until midnight the frequency of bomb bursts gradually decreased, but the duration of the bursts increased, in some instances a continuous streaming of bombs lasted for 1 minute. At midnight the activity was again reduced to a lazily rising column.

December 3, 1944.—In the morning there was a heavy eruptive column with frequent strong bursts of bombs and much lightning. The activity continued strong all day until 2 p. m., when the eruptive column suddenly subsided. From 9 p. m. to midnight the eruptive column was a thin white vapor column colored a beautiful rose pink by reflection from the incandescent lava stream below. The column was accompanied by erratic bomb bursts rising to a height of 300 meters.

December 4, 1944.—From midnight until 5 a. m., a dark eruptive column rose without noise that was audible at the camp and with bursts of bombs gradually increasing in number until activity became strong. Activity continued so for most of the day, increasing greatly at 4 p. m. and subsiding at 5 p. m. to a lazy, somewhat brownish, column (pl. 48).

December 5, 1944.—There was a lazy continuous column all day, with weak bomb bursts. The eruptive column was rather tenuous and pale brown. No noise audible at camp.

From these few days' description of a characteristic period during the Ahuán episode, it is evident that eruptive activity was erratic and unpredictable; periods of quiet, alternating with others of a dense wooly eruptive column. During these alternating and vagarious phases of eruption, the lava stream continued surging from its vent without apparent change. The only observed correlation between crater eruption and lava flow activity, if it were indeed not entirely fortuitous, was an increase in the escape of gases from the crevices at the head of the Ahuán flow. The escape was accompanied by ejection of some small incandescent bombs from these crevices, during a rapid slackening of eruptive force from the crater, observed on the afternoon of December 4. The calm and continuous flow of lava from the vent unaffected by the wide and sometimes sudden changes in the crater's activity was frequently and widely commented upon.

In the course of the next few months the apparent source of the Ahuán flow moved progressively downstream, owing to the accumulation of congealed lava over the upper reaches of the flow. This frozen roof became a jumble of blocks and scattered low hornitos, brilliantly colored with efflorescences of yellow, orange, and buff sublimates. By mid-January 1945 the flowing lava issued from a low-domed tunnel, about 150 meters from its original source. Here the open orifice was about 3 meters wide, and the lava moved at a rate of about 45 meters per hour. This small secondary vent fed a large lava front moving along the south and east sides of the base of the cone, passing Sapichu and spreading out over the surface of the older flows. The main flow then divided into two irregular tongues: one, now rather sluggish in movement, flowed toward the west as far as Quitzocho ridge and the camp; a second, actively advancing as a sinuous irregular tongue, moved toward Cerro de Pantzingo, near the northeast edge of the lava field.

Sometime in May the Ahuán flow changed its apparent vent from the low tunnel mentioned above to a lone volcancito on the Ahuán lava flow. This vent, presumably, was not a true lava conduit, but a point in the congealed crust where the lava found exit. This steep conical volcancito was about 10 meters high and situated about 100 meters southwest of the original Ahuán vent, the point where the flow first broke out from the base of the cone. The locus of the volcancito falls very nearly upon the axis of the Sapichu–main crater vents, a situation which may be entirely fortuitous. It is possible that the locus of the volcancito was determined by nothing more than a vagarious opening in the lava crust which allowed the escape of gases and lava from the lava stream flowing below. The volcancito was originally steeply conical in form, but its southwest flank soon collapsed, exposing a number of incandescent vents from which vapor escaped with a loud hissing. On its summit a chimneylike throat about 3 meters in diameter lazily issued bluish fumes. A low lava scarp passed the foot of the volcancito, extending both northwest and southeast of the volcancito itself and suggesting that the collapse of its flank was the result of a subsidence of the lava crust. To the northwest of the volcancito was an area of "cordwood" lava, grading toward the south into pahoehoe lava. To the southeast for a distance of about 300 meters, the low lava scarp showed numerous incandescent crevices hissing out bluish fumes.

The actual lava stream now issued from a crevassed and sublimate-stained low lava ridge about 100 meters east of the volcancito. At the point where it issued from beneath the crust, the stream was no more than a meter wide; and its rate of flow was 4 meters per minute. The lava stream widened rapidly, and the rate of flow decreased. No appreciable impression was made by a large rock thrown upon the surface of the extremely viscous lava that issued from the vent. Like similar flows from Parícutin, its incandescent surface was dappled by black rugose excrescences of vesicular lava, which were portions of the incipient crust torn apart by the flowing lava upon which they rode. Bluish choking fumes were given off by the flow, and occasionally the lava heaved but did not yield bursting gas bubbles.

The older Taquí flow, now covered in part by the Ahuân flow, was deeply crevassed; and one was frequently able to descend some of these crevasses to a depth of several meters and observe their structure. The Taquí flow was now apparently completely solidified, and in only a few isolated spots in the crevasses was heat perceptible. The individual flows or lava surges were 2–3 meters thick, separated by about one-third of a meter of red scoriaceous lava or baked brick-red ash. The individual flows were vesicular throughout and sometimes showed an indistinct layered structure in the middle portion of the flow.

THE CRATER ON JANUARY 22, 1945

An ascent was made to the crater rim during late afternoon of January 22. In the morning a thin eruptive column arose, accompanied by a tenuous gritty ash and a roar like a heavy surf; the column became heavier during the afternoon and rose in volutes. The north rim had an altitude, by aneroid, of 2,685 meters. At this time the crater had a single throat, about the locus of the south vent (pl. 49*A*). The south inner wall sloped directly to this vent at the angle of repose, but the north wall showed a well-defined bench and the remnants of two others.

The eruptive crater vent itself appeared to be a chimney with a throat about 3 meters in diameter, but it could not be clearly seen because of its position below the old terrace. Violent explosions in the vent induced a strong swaying motion to the summit of the cone. The explosion interval was erratic. Explosions averaged about 10 per minute. The eruptive column was blasted violently from the vent, but a few meters above the throat it expanded into its first volute and then rose more languidly. Frequently the eruptive column drifted slowly around the crater with a spiraling motion. When such a drifting column engulfed us on the crater rim, a slight odor of hydrogen sulfide was perceptible; and a frothy, semipumiceous ash fell in irregular fragments up to 10 centimeters in size. Bombs were ejected from the vent; those a meter or so across seldom rose higher than 50 meters. The bombs appeared to be semimolten, as they seemed to change shape in their flight.

The effect after dark was fearsome. The incandescent bombs left the crater throat with great speed to form a fan of fire. The larger, slow-moving bombs could be discerned easily, but the innumerable smaller bombs and lapilli were but streaks of light to the eye.

Both in daylight and after dark, compression waves in the eruptive column frequently followed the explosive bursts. When the noise was a rumbling roar, many thin compression rings followed one another in rapid succession. In spite of the tremendous explosions the noise at the crater rim could not compare to that of November 26.

THE CRATER ON MAY 27, 1945

On May 27, 1945, the crater was entered by W. F. Foshag, John V. N. Dorr, Carl Fries, Jr., and Celedonio Gutiérrez , and again to the crater rim on that night by Dorr and Fries. During this day a pure-white steam column issued from the north vent of the crater with a loud rushing noise, carrying bombs which fell on the eastern rim and slope of the cone (pl. 49*A*). At rare intervals the south vent gave off a single burst of dense black ash and many bombs. These heavy bursts from the south vent yielded a majestic eruptive column that frequently filled the entire crater and rose rapidly to a height of about a kilometer.

The two vents, as seen from the crater rim, did not seem to occupy the exact positions observed on previous ascents. The north vent was close to the northeast edge of the crater, the steep interior walls of the crater sloping directly to a chimneylike orifice. The south vent occupied more nearly the center of the crater and was much deeper and separated from the north crater by a septal ridge. The walls sloped regularly from the rim to the bottom of the crater, which showed no open orifice.

The activity of the north crater consisted of an almost continuous jet of steam issuing from the open vent with a harsh grating roar. A few highly vesicular brown bombs, like those yielded by Sapichu, were ejected to a height of 150 to 250 meters, rarely to 500 meters, above the throat of the vent. The column was slightly inclined toward the east, consequently the greater number of bombs fell on the east slope of the crater and cone. There were but rare pauses of a few seconds in the emission of vapors, the column almost immediately issuing again. The remarkable feature of this vent was the almost constant emission of white vapors and the almost total absence of ash. A slight sulfurous odor pervaded the crater.

During the 3 hours spent in the crater, the south vent showed no signs of activity, although the bomb-littered terrace and inner slopes of the crater indicated that considerable ejectamenta were thrown out during the single explosive bursts to which it was subjected. In the evening, however, Fries and Dorr observed one of these terrifying explosions from the crater rim. The eruption began with a noise like the explosion of a small charge of powder in loose ground and was immediately followed by a rapidly rising but silent heavy eruptive column, which mushroomed out overhead into a dense black pall, from which showered dark (not incandescent) bombs and ash. Previous to this explosion there was no apparent change in the crater itself to give warning of the impending blast, which occurred almost instantaneously. With this single burst, this vent resumed its inactive state.

In the upper part of the septal ridge separating the two main vents, on the slope of the larger but less active crater, were three incandescent orifices, the largest about 1½ meters across. From these issued strong jets of vapor. They were undoubtedly connected with the north vent, for their activity increased and decreased in consonance with changes in activity with this vent.

Lightning was observed at night in the occasional heavy ash column, but none was seen in the steam column.

LATE STAGE OF TAQUÍ FLOW

Some time during late June, lava activity shifted from the Ahuán vent back to the area of the Taquí vent. On July 4 the lava field about Ahuán was almost completely inactive; a broad flow of rough, clinkery lava, following the southwest base of the cone, flowed toward the northwest and still showed some slight movement. The large conical volcancito, which was a conspicuous feature of the Ahuán flow, was reduced to a pinnacled remnant surrounded by asperous lava. Abundant bluish-white fumes issued from vents in the remnant of the volcancito. A line of gas vents and sublimate-incrusted cracks marked the last channel of the lava.

Lava now issued from a crevass in a low dome near the locus of the old Taquí vents. This dome of lava had a precipitous southeast front, suggesting a scarp, perhaps owing to elevation of the crust by the injection of lava beneath. A crevass almost bisected this low lava dome. Lava issued quietly from the lower part of this crevass as a stream about a meter wide that widened rapidly down its course and split into three tongues. One could approach to within 3 meters of the apparent vent and observe the movement of the lava. It did not appear to well up from any perceptible vent but flowed from its point of origin without disturbance. As the lava moved, the surface pulled apart like viscous tar to form an asperous surface. Lower down the course of the flow, the surface was pulled into loose congealed clinkers that rode along the surface of the flow.

Above the apparent lava vent, the dome showed incandescent crevasses from which choking bluish-white fumes hissed; the vents and the crevasses were colored gray or buff by deposited sublimates.

To the north east of this active lava flow was a high irregular cone of lava, an inactive volcancito.

On July 31, our last visit to Mesa de Los Hornitos, the lava dome from which the flow issued remained relatively unchanged, although the lava now issued not only from the crevasse, as previously, but had also broken out on the opposite side of the dome and from the foot of the scarp of the dome. A short flow was moving from the original vent and another from the vent at the base of the scarp, but the principal flow issued from the dome opposite the original vent and formed a long lava stream that extended to the north for more than a mile. The Ahuán area showed no apparent activity, but the area was colored with a large patch of yellowish sublimates.

In early July the crater showed greater than normal activity and appeared to have three vents. The north vent was in almost continuous activity, and its eruptive column was slightly inclined toward the east. The south vent showed sporadic heavy bursts canted toward the south and sometimes yielded billowing incandescent ash. A west vent exploded at irregular intervals, yielding bursts of bombs slanted westward, showering bombs on Mesa de Los Hornitos. The heavy activity from the crater precluded an ascent to the crater rim.

During this period, sharp pointlike discharges of lightning, accompanied by a sharp shotlike thunder, were not uncommon in the eruptive column.

In late July the crater showed a funnel-shaped form, surrounded on the west, north, and east by a broad terrace (pl. 51). The single eruptive vent probably represented the more persistent south vent. During the brief interval when little ash issued from the crater, it could be seen that the bottom of this vent was occupied by three, or perhaps more, incandescent orifices, from which the vapors escaped with great force. For a brief period two small incandescent orifices, emitting small plumes of dirty vapor, appeared on the inner north slope of the crater, below the encircling terrace.

SUMMARY OF THE TAQUÍ PERIOD

Although the southwestern flank of the cone showed a minor emission of lava on August 26, 1943, persistent activity did not begin in this area until January 7, 1944, with the outbreak of the Taquí vents. This outbreak immediately followed the complete cessation of activity in the Sapichu vent. The Taquí orifice became the most persistent and long lived of any of Parícutin's lava vents. Emission of lava from the Taquí vents alternated with lesser flows from the Ahuán vent, an orifice corresponding to the earlier Pastoriu and Mesa del Corral flows and which was situated directly opposite the Sapichu vent and presumably upon the same fissure. Because activity from the Taquí vents alternated with that from the Ahuán vent, we proposed to include, for simplicity, the Ahuán activity in the Taquí period.

Taquí's activity began with the surging of lava from three small vents at the southwest base of the cone, which were soon, however, engulfed and covered by their own lava. Numerous flows and tongues of lava issued from these vents, most of which did not appear directly at the locus of the vents themselves but broke out on the surface some distance away after first flowing for variable distances beneath the congealed crust. The largest of these flows, which we have called the Taquí flow, has a total length of about 10 kilometers and covers an area of arable land belonging to San Juan Parangaricutiro and Parícutin and including these two towns themselves. It is difficult to estimate the total ejectamenta and lava during the Taquí period, because the average thickness of the Taquí lavas is not well known. Over Llano de Quitzocho it reached a thickness of about 60 meters. The area covered by the flows of this period, to July 1945, was 17¾ square kilometers. At the end of this period the cone had an elevation of about 340 meters above the original terrain and a diameter at its base of 1 kilometer. The diameter of the crater was about 0.4 kilometer.

The crater showed greater activity during the Taquí period than the preceding Sapichu period but considerably less than during the Quitzocho period. During the Taquí period, explosive activity was erratic, sometimes for very brief periods reaching a violence equal to activity during the Quitzocho period but frequently being reduced to weak emissions, even less than that shown during the Sapichu period. Rarely was the eruptive column heavily charged with ash, and it frequently consisted of apparently pure steam. Bomb and ash types ejected were similar to those of the previous periods.

338669 O—55——9

During the Taquí period, the cone showed little increase in elevation. Slight increases, owing to an increment of new ejecta, were offset by slides in the crater and by rainwash. These variations induced little change in the appearance of the cone. The crater line showed some notable changes, particularly the north and south crater rims, owing to scouring by the north and south crater vents, sometimes resulting in a marked saddle shape to the crater rim. The only notable changes in the exterior form of the cone were the minor slumps induced by the initiation of the Taquí and Ahuán flows.

The most striking feature of the Taquí period was the growth of volcancitos and hornitos on the surface of the Taquí flow and, to a much lesser extent, on the Ahuán flow. These owed their origin, perhaps, to the fortuitous circumstance that the actual lava vents became buried under their own flows, allowing the molten lava to move through channels beneath a crust, rather than as overriding tongues as in the previous flows. Emanations from the subcrustal lava were then forced to find their escape through vagarious channels in the crust itself. These emissions contained combustible gases, as demonstrated by the striking flames which were frequently observed over both the volcancitos and hornitos. The fountaining of gas-charged lava from crustal vents to form volcancitos presented a beautiful spectacle. The short flows that issued from the volcancitos yielded a smooth hummocky pahoehoelike flow or an unusual "cordwood" form of lava.

The lavas of the Taquí and Ahuán vents showed no appreciable differences from those of previous flows, yielding the usual rubble and clinker-covered surface. The only striking difference was in the Parangaricutiro tongue of the Taquí flow, whose torn and jagged appearance is in marked contrast to other lavas. This may be due, perhaps, to its prolonged period of flow. Four and one-half months elapsed from the time the lava issued from the vent until it reached the outskirts of San Juan Parangaricutire and changed its characteristic structure. Perhaps an essential difference between the Parangaricutiro tongue and other tongues and flows was its mode of advance much of which took place, not as overriding tongues but as subcrustal flow. During this time, the lava presumably underwent some crystallization and undoubtedly lost much of its volatile contents. After a pause and apparent quiescence of about 3 months, the Parangaricutiro tongue broke out from beneath its cover of rubble and clinkers at Turímbiro, near the base of Cerro de Equijuata, or about 5 kilometers from its original source.

It was during the Taquí period that there were occasional opportunities to ascend the cone and observe the configuration and activity of the crater. The presence of a persistent and permanent vent near the southwest edge of the crater, so frequently apparent in the position of the eruptive column, was confirmed, as was also the lesser but still important northeastern vent. There were also ephemeral vents. The inner configuration of the crater depended largely upon the relative activity of these separate orifices as well as upon the intensity of the activity itself. The actual orifices of the vents were surprisingly small, considering the size of the emitted eruptive column. The character of the eruptive column was also conditioned by the inner configuration of the crater. Where the eruptive orifices were open, a vapor column free of, or only slightly charged with, ash resulted. If the eruptive orifice was choked with ash and debris, frequent ash slides took place into the vent; or where the eruptive column scoured the adjacent wall, the eruptive column was charged with ash. When the eruptive vents were open, the small quantity of ash carried by the eruptive column consisted of brown shredded slag, scoured from the molten lining of the crater vent; and the eruptive column had a pale-brownish and "gritty" appearance. When the vents were choked, the ash consisted of a variety of forms including shredded slag, triturated material, spalls, and other forms, that is to say, such material as made up the cone itself.

During the 18 months that the Taquí period was under observation, it became evident that no further unusual change in the activity of the volcano was likely to take place, that the volcano had settled down to a comparatively regular routine, and that its formative period had drawn to a close. It was no longer an infant volcano but a mature, volcanic apparatus. Activity, although continuous, was considerably reduced in force; and the cone acquired such a degree of stability that it became difficult to change radically its configuration or size. Parícutin was now an established volcano. Its period of youth and development could be considered closed.

GENERAL EFFECTS

EFFECT ON LIFE

The effect of the advent of the volcano on life in the region, while not a geological subject, presents some interesting features perhaps worthy of note. The influence of the volcano on human affairs within the immediate volcanic zone can be easily imagined and need not be dealt with here. The destruction of homes and rich farmlands was an overwhelming catastrophe for the folk that inhabited the area.

The effect upon wildlife, although less evident, yielded some interesting observations. The advent of sudden and violent change in a previously placid area brought about a rapid diminution of the animal population of the region. But it appears that fright was not an important factor in this change. Such animals and birds as persisted in the region during the early and most violent period of the volcano showed no fear of and even seemed totally oblivious to the terrible events that followed each other in quick succession.

The first animals to disappear from the region were the deer and rabbits, and with them, to a large extent, went the coyotes, owing, no doubt, to the disappearance of their food supplies. As long as the pine and oak trees remained alive, squirrels and jays persisted and left only when the supply of pine cones and acorns vanished. Smaller birds, like creepers, also persisted, feeding upon the insects still abundant in the forest or blown in by the winds. Eventually these, too, left the area, except for a few occasional stray ones that passed through. The winds brought in numerous bugs of various kinds, which the falling ash battered to the ground. These bugs, consisting of moths and butterflies, grasshoppers and leafhoppers, and other forms, collected in sheltered pockets or in the shallow rills in the ash, and became a constant source of food for such animals as remained. Even after 2 years of activity field mice and foxes persisted, and their tracks could be seen on the ash, even on the ash over recent lava flows. Crows were seen almost daily about the volcano and frequently alighted on the cone, during falls of ash and bombs. It was discovered that the slopes of the cone yielded an abundant supply of bugs, which undoubtedly was the principal attraction for the crows.

Reptilian life was not common. A large lizard apparently found a hole in the warm lava a congenial environment, with abundant food at his door. The few snakes we observed were obviously having a hard time of it, the loose ash not being particularly suited to their manner of locomotion. Frogs died and desiccated in the ashy environment.

Particularly striking was the apparent lack of interest or fear shown by the birds and animals to even the most violent outburst of the volcano. Horses and dogs evinced no interest whatever. On one occasion the dog of one of the natives accompanied us to the summit of the cone, and while we watched events with considerable trepidation, curled up in the ash and went to sleep. The crows, previously mentioned, during their forays to the cone, showed no apparent concern for explosive bursts from the crater.

The resistance of plantlife to ash varied greatly. During the heavy ash falls of 1943, the trees of the surrounding forests were totally defoliated and appeared dead. After the cessation of heavy ash fall, the oaks and madroñas frequently put out new leaves, but the pines remained dead. Ferns, particularly bracken, showed the greatest resistance to ash. Some herbaceous plants, like chicalote (an argemone), a nicotiana and a gillia, and a coarse rhizomic grass, were able to push through a heavy cover of ash and thrive. After the first seedfall of pines, numerous seedlings sprang up and throve. Pines were the first of the forest trees to spring up in the devastated area.

EFFECT ON AGRICULTURE

Where a heavy blanket of ash covered the fields, the land was lost to agriculture. Corn planted in the ash germinated well but soon withered and died. Fine ash, falling on crops, frequently had a deleterious effect. For instance, fine ash sifting into avocado blossoms inhibited pollenization, and the crop failed. It was reported to us that the sweetpotato plantings at Tancítaro throve, but the plants failed to set tubers. Abrasion of ash on the sugar cane about Los Reyes allowed access to fungi, and the crop failed.

On the other hand, a moderate ash fall proved beneficial. At Zacán, where the ash was only a few centimeters deep, the wheat grew as never before and yielded bumper crops. Although the ash probably contained some nutrient value and acted as a soil conditioner, the principal effect was probably due to its action as a moisture-retaining mulch. A Capacuaro the corn crop, owing to the increment of ash to the soil, proved extraordinarily good.

Great damage was done to the irrigation system about Los Reyes where the ash-laden waters filled the ditches and covered the fields with debris.

The heavy rains of the wet season rapidly washed the ash cover from the open slopes and carried it to the lower valleys. It appears, therefore, that the lower lands will be lost to agriculture for some time to come. The lack of herbaceous cover and the accelerated scouring, owing to the ash-ladened waters, will erode the original soil of the slopes unless judicious plowing is undertaken before erosion removes the top soil. On many of the fields the thickness of ash has already been so reduced that it is feasible to plow the ash cover under and mix it with the original soil. This increment of ash should prove beneficial to the soil.

EFFECT ON HYDROLOGY

The blanket of ash that covered a wide area was washed by the rains during the rainy season into the arroyos. In many cases this ash was deposited in the arroyos and in extreme cases completely filled them. During periods of heavy rainfall, the waters were heavily laden with ash. Samples collected in Arroyo de Nureto near Angahuan during a heavy rain were about one-half by volume ash. The following table gives some data on water samples from the Río Itzícuaro, near Los Reyes, collected by Ing. Vicente Villaseñor, of the Comisión Nacional de Irrigación, at Morelia.

Data on some ash-laden waters

Sample	Date collected	Density	Solids, in percent	Water, in percent
1	Aug. 25, 1943	1.604	60.35	39.65
2	Aug. 29, 1943	1.883	71.20	28.80
3	Sept. 1, 1943	1.013	7.21	92.79

The movement of this heavily laden water produced some interesting effects. According to Ing. Villaseñor, the transporting power of the Río Itzícuaro was greatly increased, and large boulders that rested for years in or along the stream bed were easily transported downstream by the river waters. Many of the lands bordering the river were littered with transported boulders, and about San Juan Parangaricutiro some of the fields below arroyos, previously free of cobbles, were littered with boulders brought down by the ash-charged streams. More striking was the finding of boulders in the crotches of trees, mixed with the flotsam of a flood; grass, twigs, and sticks of wood, as well as ash and lapilli, indicating that they were transported during a flood of ash-laden waters.

On the steep slopes of such hills as Cerro de Capatzun, the ash cover was rapidly removed by rainwash, exposing the original soil surface below. Rills and small arroyos developed rapidly in this original soil, owing in part to lack of its original cover of vegetation but also, no doubt, to the scouring effect of the ash-laden waters. Beneath pine trees in many forested areas, an accumulated mat of pine needles in the ash inhibited erosion, and the ash blanket was then more resistant to erosion.

At times, during heavy rainfalls, deep gullies or arroyos formed during a single storm. One such arroyo is shown in plate 47*B*. A single storm could not only excavate a deep arroyo but would sometimes scour the old surface to a depth as much as a meter. In the walls of such arroyos, the layered deposition of ash was well demonstrated, and it was interesting to observe intercalated tongues of cobbles and boulders brought down from nearby slopes of neighboring hills by the ash-laden arroyos.

Because the lava flows completely filled many of the valleys, numerous small arroyos from the side hills were blocked, and ash transported during the rainy season was deposited to a considerable thickness in the small basins thus formed. A line of steam fumaroles in the lava sometimes indicated the original course of the arroyo. These fumaroles disappeared during the dry season.

According to some of the natives of the region, many of the intermittent streams and springs now discharge much more water during the dry season than during previous years. This, they state, is particularly true of the area west of the volcano. It was in this direction that the heaviest ash falls occurred. The porous nature of the ash has, undoubtedly, acted to conserve the rainwaters of the wet season. It was frequently noted that even after protracted dry spells the ash remained moist at a very shallow depth.

Mudflows on the steep slopes were rare and then of minor proportions. Occasionally a blanket of ash became sufficiently saturated to flow down the slopes, but in general the ash-covered slopes were remarkably stable. The tilt of dead pine trees on such slopes as Cerro de Canicjuata indicates a slow downhill creep of the ash blanket.

EFFECT ON MICROCLIMATOLOGY

Because no weather data seem to have been collected in the area previous to the volcano, no precise changes in the local climate can be specifically noted. The altitude of the area lies between 2,000 and 2,500 meters except for the high Cerros de Tancítaro, the highest point in Michoacán (3,845 meters), which lies immediately to the southwest of the volcano. From this region, the terrain slopes irregularly to the Pacific coast. The area is not well sheltered from the winds that sweep in from the west. The seasons in Michoacán, as in other parts of southern Mexico, are divided into wet and dry periods. The rainy season usually lasts from early June to late September when showers or heavy downpours of rain occur almost daily, frequently accompanied by thunder and lightning. The days begin clear and cloudless, but at midmorning fleecy clouds begin to form. During late morning or early afternoon, the rains occur, the sky becoming clear again in late afternoon. The general concensus of opinion among the natives of the region is that there has been no apparent change in the character of the summer storms or in the quantity of precipitation. During the heavy ash falls of early 1943, however, it was frequently noted that the first cloud formation took place below the heavy drifting ash cloud (pl. 23*A*) and was soon followed by cloud formation in all other horizons. There was no positive indication, however, that the ash column initiated or even accelerated any storms. Not infrequently gentle rains of mud were experienced under the heavy pall of drifting ash, sometimes when no rain was apparent in other directions, and even during the dry season. These rains were attributed to condensation of steam in the eruptive column. Rains in the immediate vicinity of the volcano, as at the camp at Cerro de Canicjuata, frequently showed an acid reaction to litmus paper, while rains somewhat farther away, as at San Juan Parangaricutiro, did not. The acid rains had a hardly perceptible sour taste.

During the rainy season, clouds and fogs drifted in from the west. Occasionally, when the cloudbanks reached the cone, their advance was temporarily halted by the rising column of heated vapors sometimes for a period of an hour or more (pl. 41*B*).

Before the advent of Parícutin, the immediate neighborhood was subject to heavy frosts, with frequent development of hoarfrost in the winter. Snowfalls on Cerros de Tancítaro were not unusual. During the period 1943–45, we observed no hoarfrost at Cerro de Jarátiro or other nearby points. The natives agreed that this condition was unusual, because previous winters always brought frosts to Cerro de Jarátiro. Nor were there snowfalls on Cerros de Tancítaro during this period.

One of the most striking effects of the hot lava flows was the development of considerable air turbulence, manifesting itself most obviously in numerous whirlwind columns. As many as ten could be observed at one time. Usually they formed over the ash-covered lava flows. Some rotated rather languidly, others revolved with such force as to tear limbs from the pine trees bordering the flows. Some remained almost stationary; others moved their positions slowly; many persisted for half an hour or more.

An almost continuous updraft of air toward the cone was observable, particularly in the rising steam column from the fumaroles. Frequently, in the hush of the evening, these vapors collected from all directions to fill the basin about the foot of the cone. Rarely the updraft up the slopes of the cone was sufficiently rapid to form whirlwinds that extended from the slopes of the cone to the lowering eruptive column. This occurred, particularly, when an evident downdraft from the crater met an updraft following the slope of the cone.

LITERATURE CITED

Bullard, F. M., 1947, Studies on Parícutin volcano, Michoacán, Mexico: Geol. Soc. America Bull., v. 58, p. 433–449.

Carreño, Alfonso, de la O, 1943, El Volcán de Parícutin en las primeras fases de su erupción: Irrigación en México, v. 24, no. 4, p. 49–80.

Flores, Teodoro, and others, 1945, El Parícutin, Estado de Michoacán: México Univ. Nac., Inst. Geología Bol. 37, Mexico City.

Foshag, W. F., and Henderson, E. P., 1946, Primary sublimates at Parícutin volcano: Am. Geophys. Union Trans., v. 27, p. 685–686.

González R., Jenaro, and Foshag, W. F., 1947, The birth of Parícutin: Smithsonian Inst. Ann. Rept. for 1946, p. 223–224.

Hatt, Robert T., 1950, A bibliography of Parícutin volcano: Mich. Acad. Sci. Papers, v. 34, p. 227–237.

Ordóñez, Ezequiel, 1943, El Volcán de Parícutin, Comisión Impulsora y Coordinadora de la Investigación Científica, Anuario 1943, p. 241–300.

——— 1945, El Volcán de Parícutin: Comisión Impulsora y Coordinadora de la Investigación Científica, Mexico, 138 p.

Ordóñez, Ezequiel, 1947, El Volcán de Parícutin: Editorial Fantasia, Mixcoac, D. F., 181 p.

Perret, F. A., 1912, The flashing arcs: a volcanic phenomenon: Am. Jour. Sci., 4th ser., v. 34, p. 329–333.

Robles Ramos, Ramiro, 1943, El Volcán de Parícutin y el neo-volcanismo Mexicano: Irrigación en México, v. 24, no. 4, p. 81–122.

Sánchez, Pedro, 1935, Importancia Geográfica del "Eje Volcánico": Inst. Pan Am. Geog. and Hist., Pub. 11, 13 p.

Segerstrom, Kenneth, 1950, Erosion studies at Parícutin, State of Michoacán, Mexico: U. S. Geol. Survey Bull. 965–A, 164 p.

Stearns, Harold T., and MacDonald, Gordon A., 1942, Geology and ground-water resources of the island of Maui, Hawaii: Territory of Hawaii, Division of Hydrography, Bull. 7.

Trask, Parker D., 1943, The Mexican volcano, Parícutin: Sci., new ser., v. 98, no. 2554, p. 501–505; reprinted in New York Acad. Sci. Trans., ser. 2, v. 6, no. 12, 1943.

Waitz, Paul, 1943, El nuevo volcán de Parícutin: Irrigación en México, v. 24, no. 4, p. 37–48.

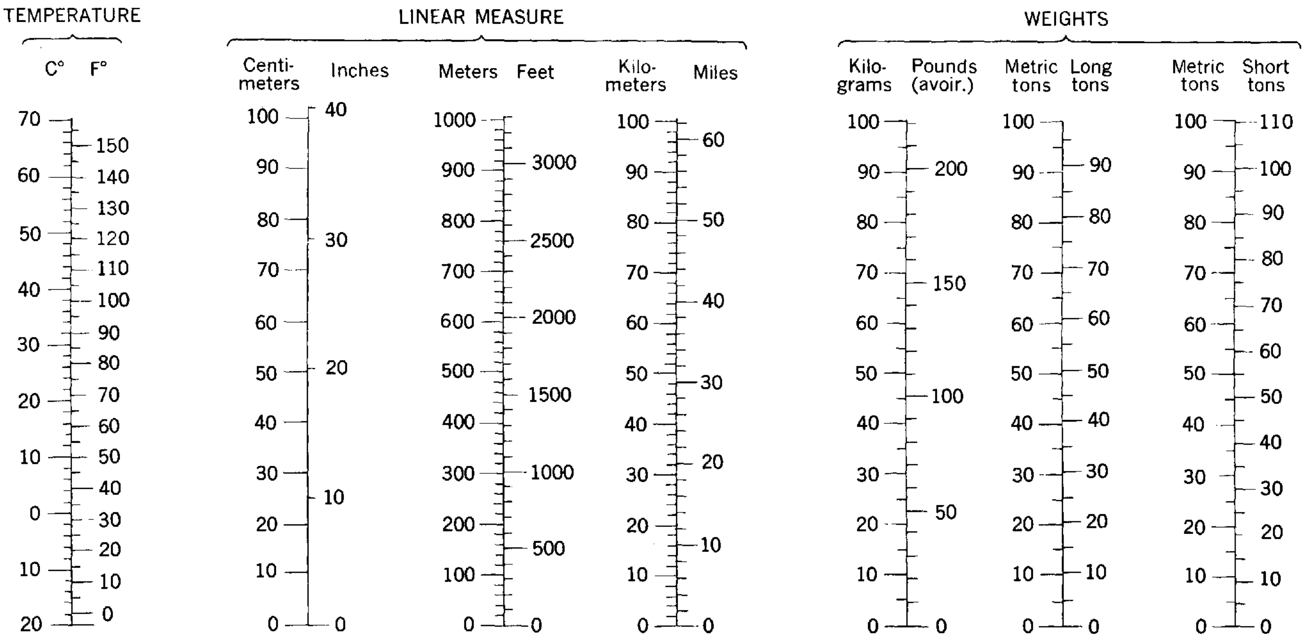
White, D. E., 1945, Parícutin's cyclic activity: Am. Geophys. Union Trans., v. 25, p. 621–628.

Wilcox, R. E., 1947, The activity of Parícutin volcano from September 18 to November 30, 1946: Am. Geophys. Union Trans., v. 28, p. 567–569.

Williams, Howel, 1950, Volcanoes of the Parícutin region, Mexico: U. S. Geol. Survey Bull. 965–B, p. 165–279.

Zies, E. G., 1946, Temperature measurements at Parícutin volcano: Am. Geophys. Union Trans., v. 27, p. 178–180

METRIC EQUIVALENTS



1 cm. = 0.3937 inch
1 inch = 2.5400 cm.

1 meter = 3.2808 ft.
1 ft. = 0.3048 meter
1 sq. meter = 1.20 sq. yd.
1 hectare = 2.47 acres
1 cu. meter = 1.31 cu. yd.

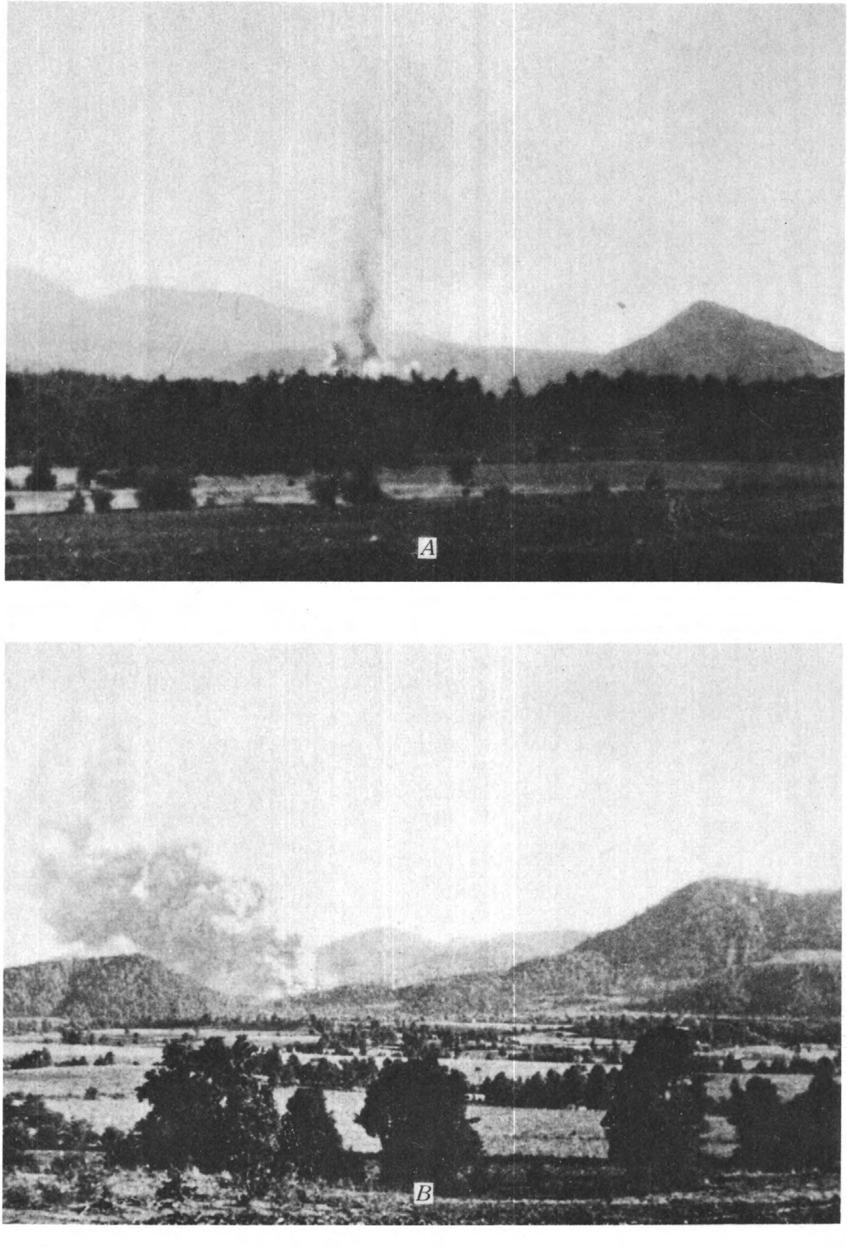
1 km. = 0.6214 mile
1 mile = 1.6093 km.

1 kg. = 2.2046 lbs.
1 lb. = 0.4536 kg.

1 metric ton = 0.9842 long ton
1 metric ton = 1.1023 short tons
1 metric ton = 2205 lbs.
1 long ton = 1.0161 metric tons
1 short ton = 0.9072 metric ton

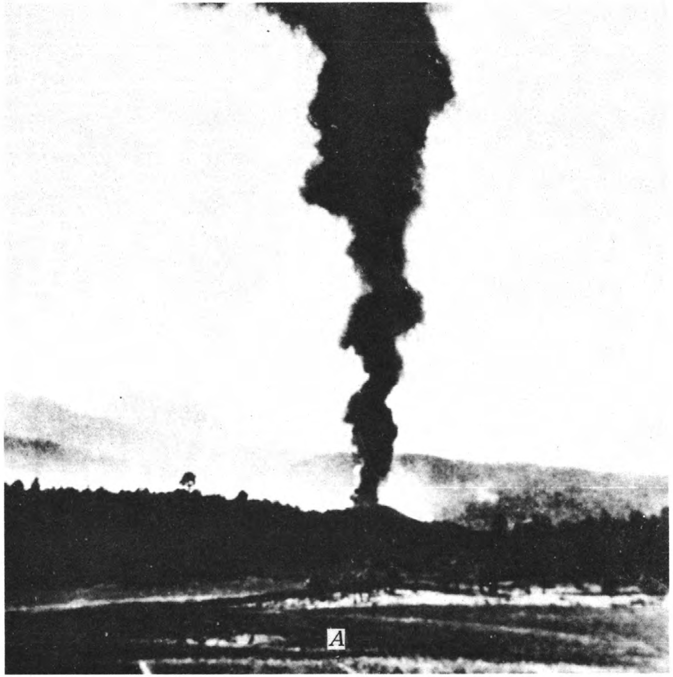
INDEX

PLATES 16–51



ERUPTIVE COLUMN OF PARÍCUTIN VOLCANO

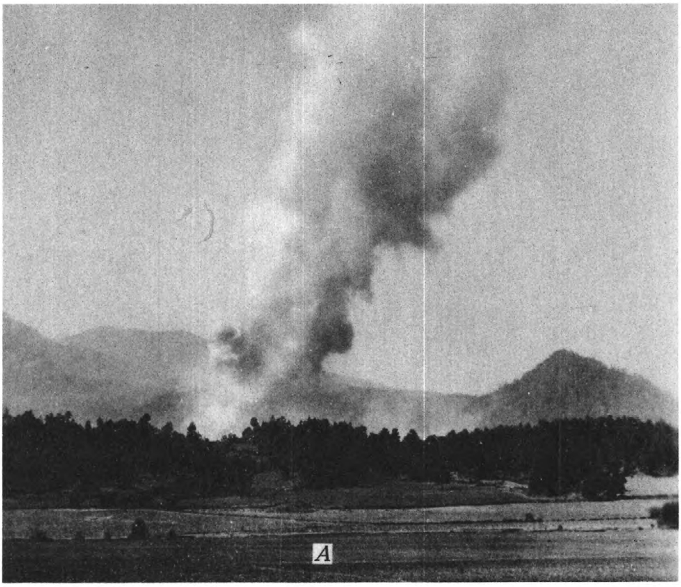
A.—February 20, 1943. The new volcano broke forth in the valley of Quitzocho-Cuiyúsuru, which lay between Cerro de Jarátiro (left), Cerro de Camiro (far center), and Cerro de Canicjuata (right). Parícutin village lies near the foot of Cerro de Canicjuata. The fields of San Juan Parangaricutiro are in the foreground. Taken from Ticuiro, near San Juan Parangaricutiro, at 5 p. m.
B.—Same area photographed one-half hour later.

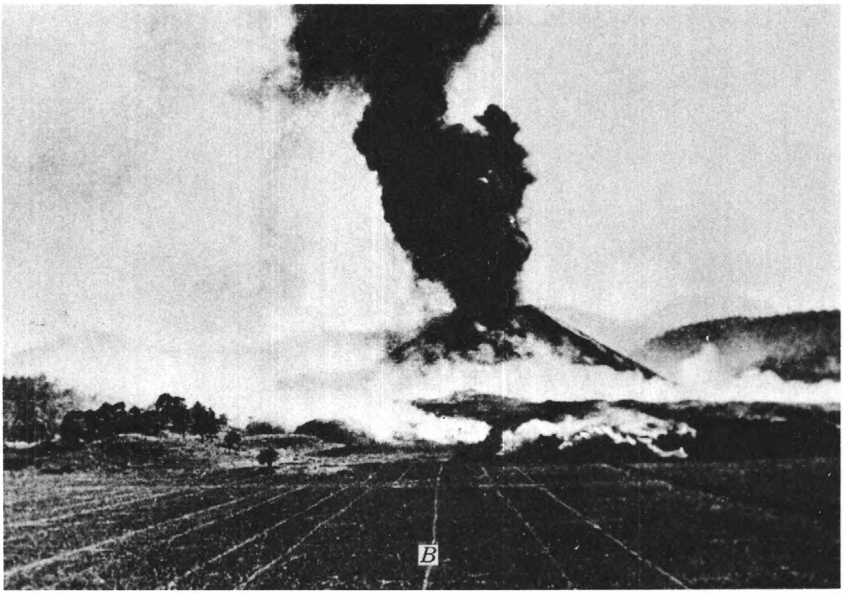


THE NEW CONE

A.—February 21, 1943. The new cone, about 30 meters high, appears above the treetops. Taken from the northeast. Photograph by Salvador Ceja.

B.—February 22, 1943. The new cone viewed from the northeast. Great quantities of ejected bombs and lapilli caused the new cone to grow rapidly. Vapors of the first (Quitzocho) lava flow are around the base of the cone. Cerros de Tacítaro in the right background. Photograph by Rufus Morrow.

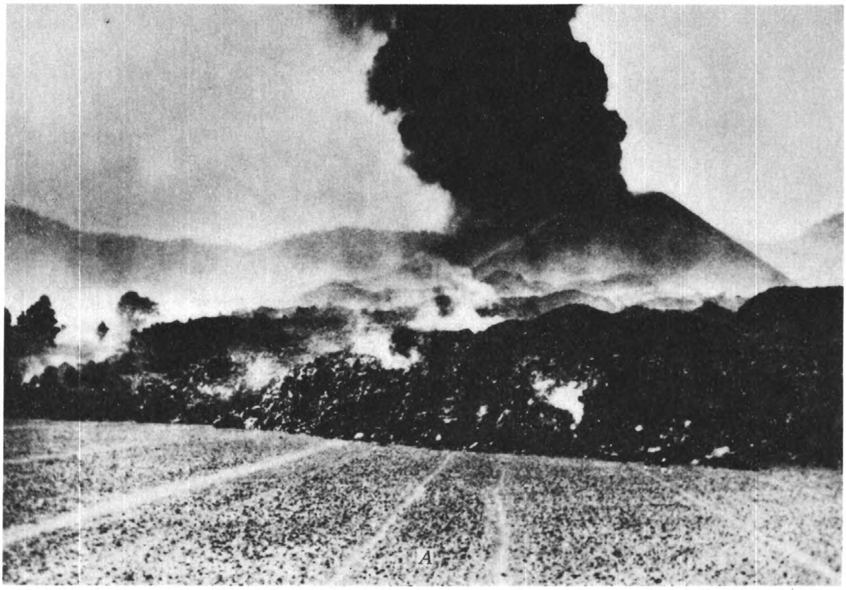




ERUPTIVE COLUMN

A.—February 24, 1943. Vaporous eruptive column with little ash. Taken from the northeast. Photograph by Ezequiel Ordóñez.

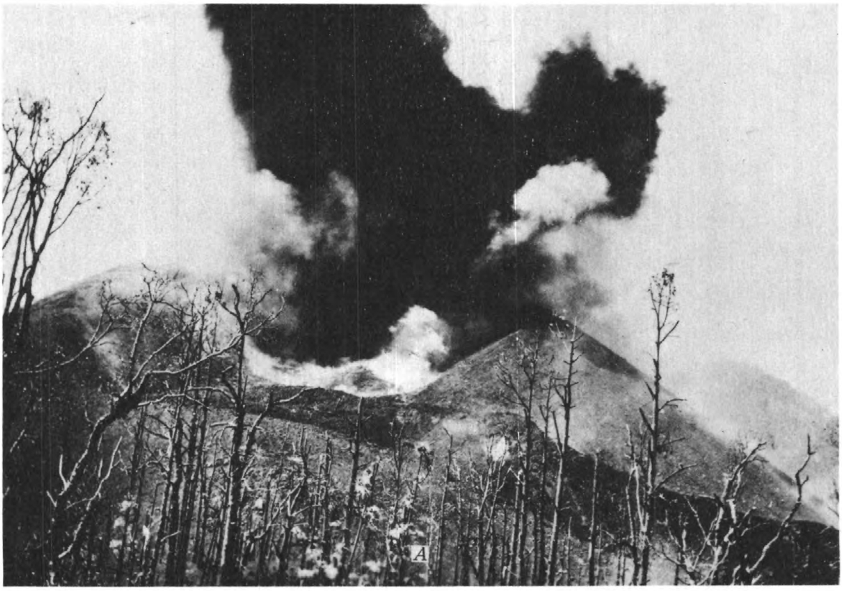
B.—February 23, 1943. Heavy emission of bombs with moderate eruptive column. Llano de Quitzocho in the foreground; Quitzocho lava flow with abundant fumaroles in the middle ground. View from the northeast. Photograph by Ramiro Robles Ramos.

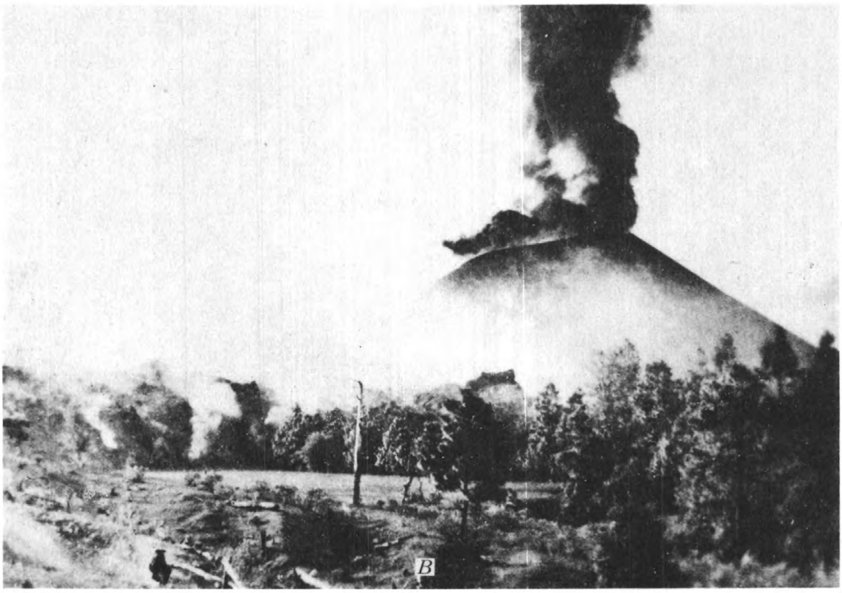


HORSESHOE-SHAPED CONE AND QUITZOCHO LAVA FLOW

A.—March 2, 1943. Heavy bomb and lapilli emission. The horseshoe shape of the cone is apparent. Quitzocho lava flow in middle ground. Note the sparse cover of ash in the cultivated fields. Taken from the northeast. Photograph by Instituto de Geología.

B.—March 5, 1943. Air view of the cone from the northeast. Quitzocho flow in the foreground with fumaroles around its periphery; Cuiyúsuru, right; Teruto, middle ground. Photograph by Ezequiel Ordóñez.

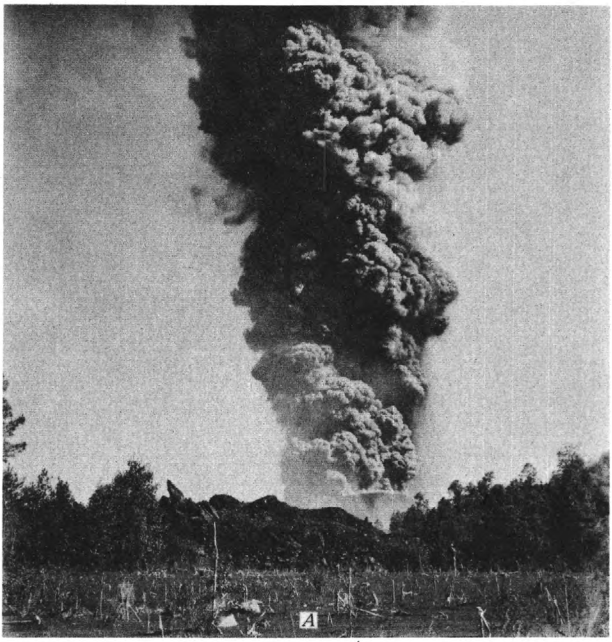


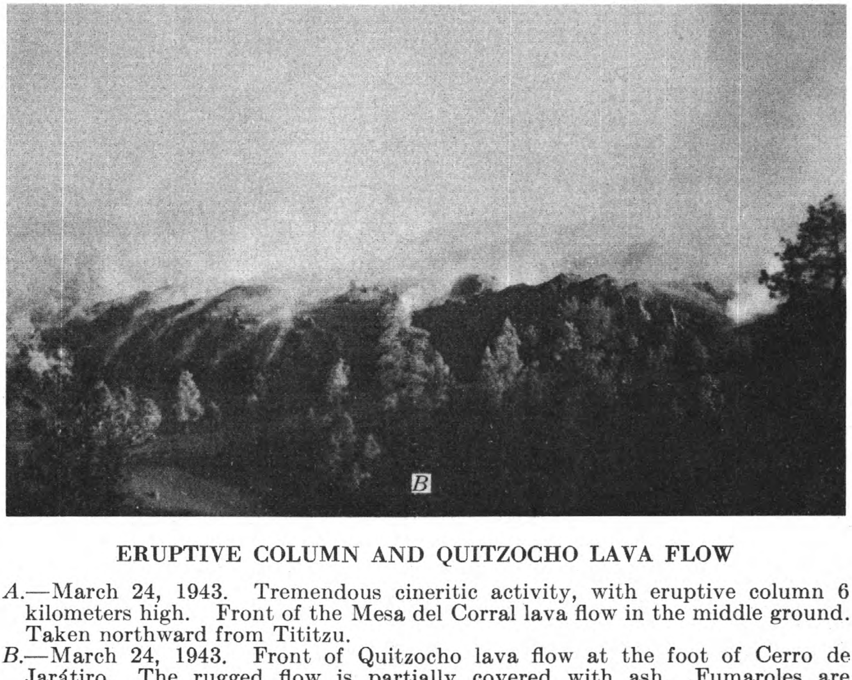


QUITZOCHO LAVA FLOW

A.—March 10, 1943. Breached eastern side of cone showing the crater and hummocky surface of Quitzocho lava flow. In the foreground are the remains of a forest destroyed by bomb and lapilli falls. Photograph by Ezequiel Ordóñez.

B.—March 20, 1943. The Quitzocho lava flow has almost reached its maximum extent at the foot of Cerro de Jarátiro. The cone is still asymmetrical owing to repeated breaching. Taken from the eastern foot of Cerro de Jarátiro.

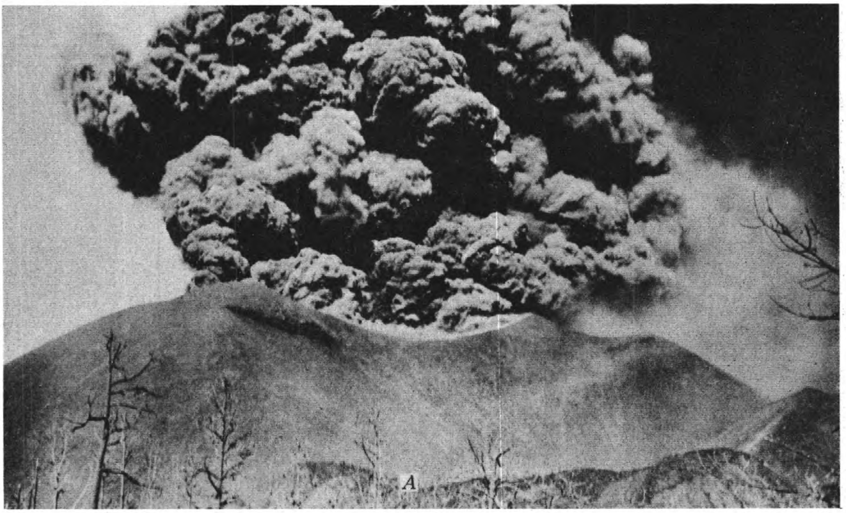


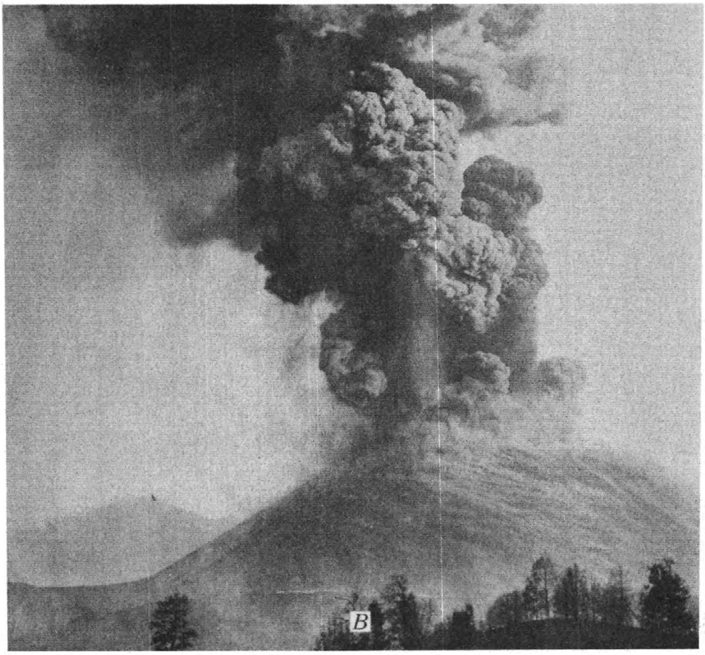


ERUPTIVE COLUMN AND QUITZOCHO LAVA FLOW

A.—March 24, 1943. Tremendous cineritic activity, with eruptive column 6 kilometers high. Front of the Mesa del Corral lava flow in the middle ground. Taken northward from Tititzu.

B.—March 24, 1943. Front of Quitzocho lava flow at the foot of Cerro de Jarátiro. The rugged flow is partially covered with ash. Fumaroles are situated about its periphery.

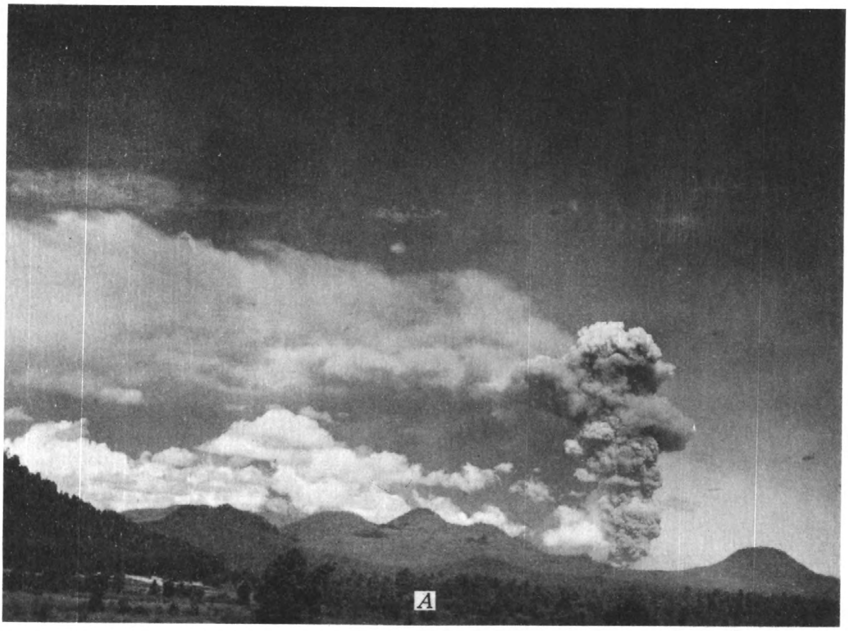


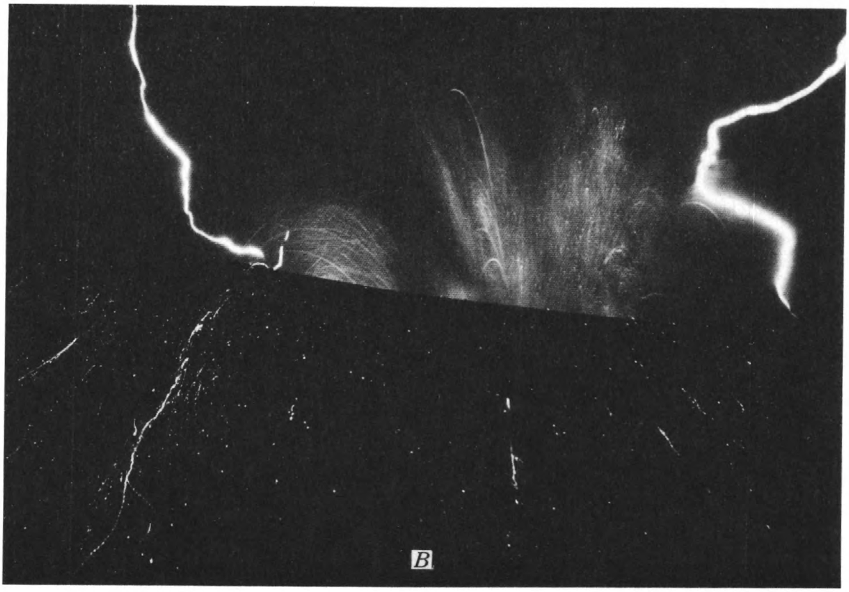


HEAVY CINERITIC ACTIVITY

A.—April 22, 1943. The breached cone, now partly restored, and the inner cone or "ombligo." Very heavy cineritic activity. Taken from the south. Photograph by L. C. Graton.

B.—May 24, 1943. Heavy cineritic activity, accompanied by abundant bombs. Taken from Cerro de Jarátiro.

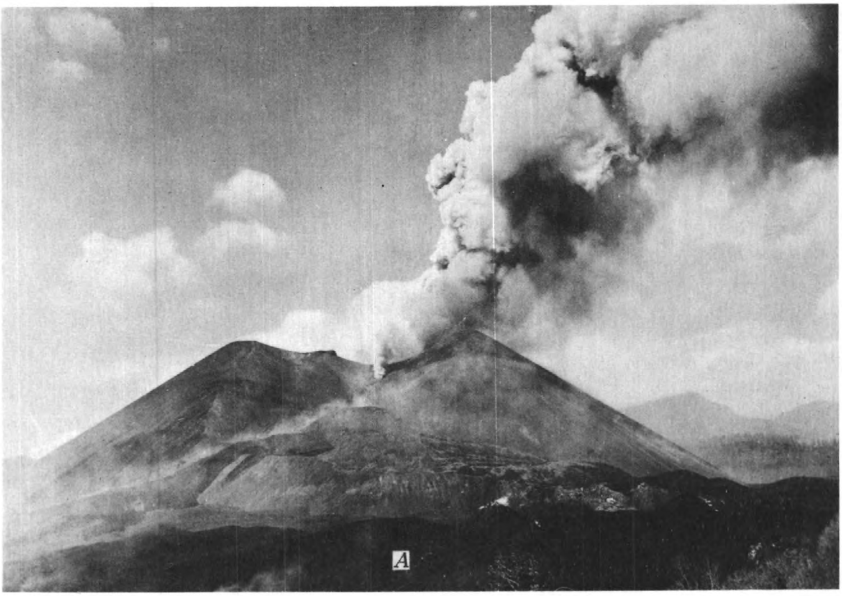


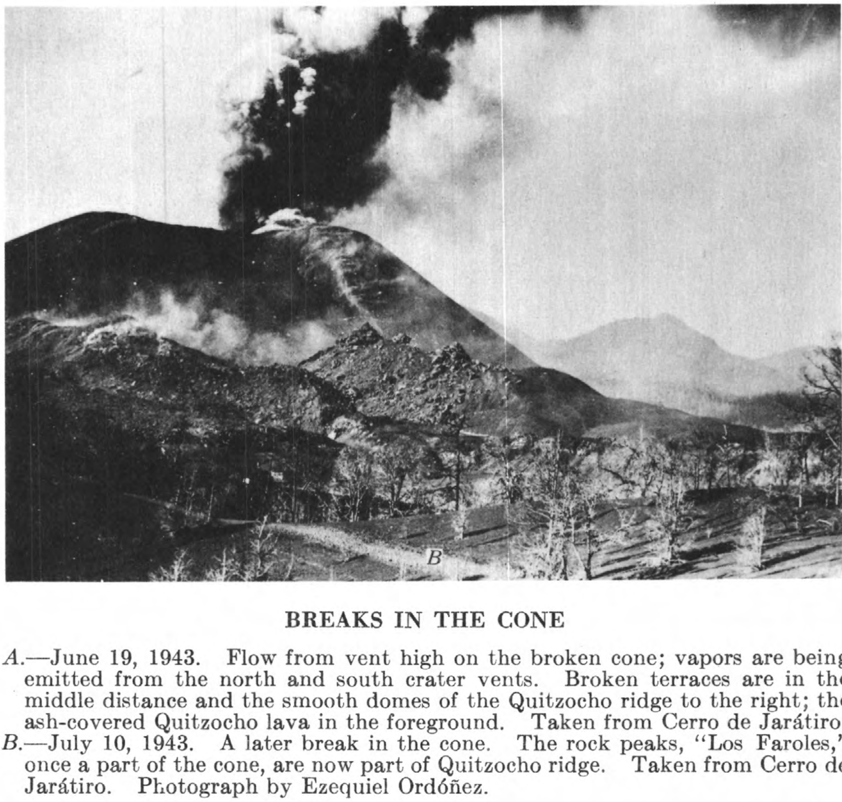


ERUPTIVE COLUMN

A.—June 9, 1943. Eruptive column from the Uruapan highway. Plume of drifting ash to the south and clouds forming beneath it. Extinct volcanic cones in the middle distance. Taken from the east.

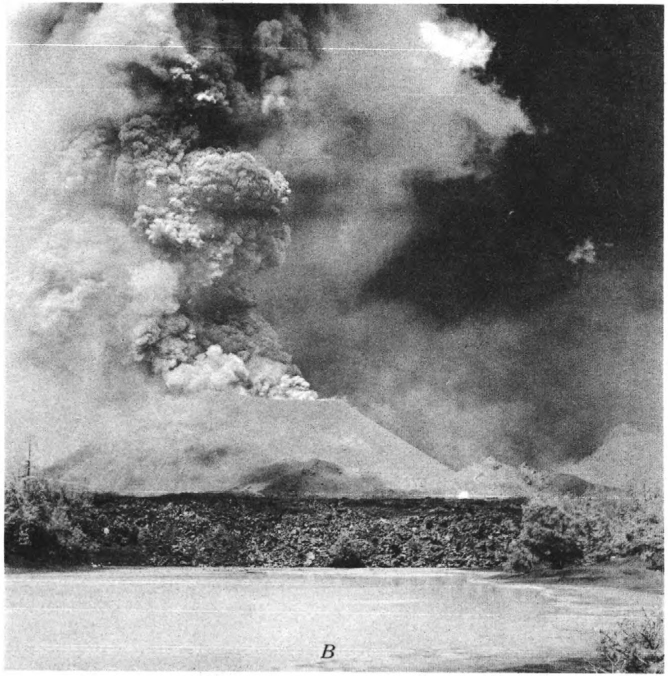
B.—May 25, 1943. Lightning flashes were frequent in the dense swiftly rising eruptive column. Photograph by Rafael García.





BREAKS IN THE CONE

A.—June 19, 1943. Flow from vent high on the broken cone; vapors are being emitted from the north and south crater vents. Broken terraces are in the middle distance and the smooth domes of the Quitzocho ridge to the right; the ash-covered Quitzocho lava in the foreground. Taken from Cerro de Jarátiro.
B.—July 10, 1943. A later break in the cone. The rock peaks, "Los Faroles," once a part of the cone, are now part of Quitzocho ridge. Taken from Cerro de Jarátiro. Photograph by Ezequiel Ordóñez.

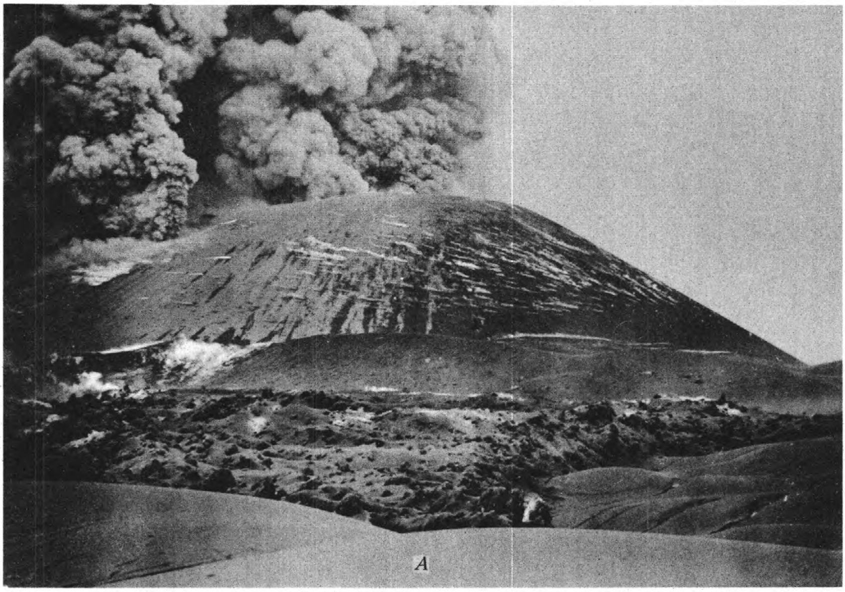


PARTLY RESTORED BROKEN CONE

CINERITIC ACTIVITY

A.—June 28, 1943. The broken cone, viewed northeastward from Cerro de Curupichu after the break of June 10, is now partly restored. Lava issues from a vent high on the flank of the cone (the Lagunita flow) and spreads out in the valley below. Photograph by Arno Brehme.

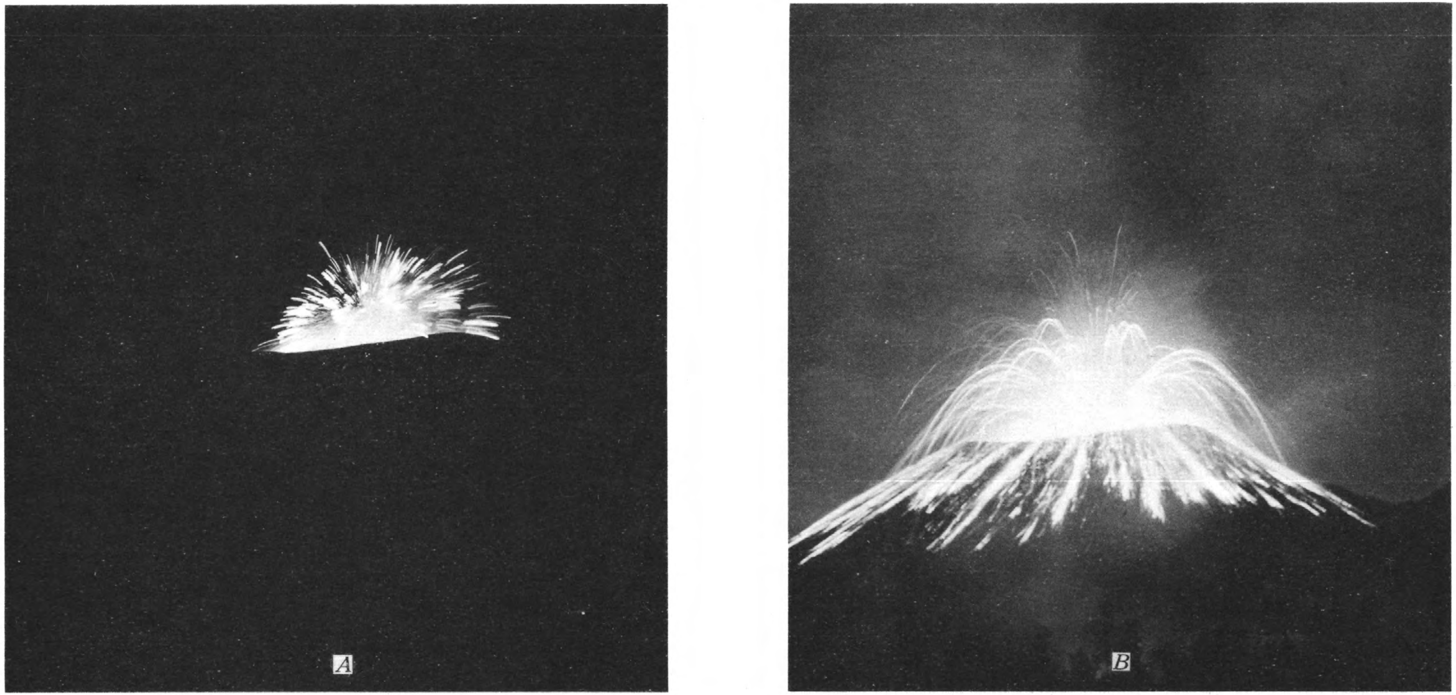
B.—July 25, 1943. Heavy cineritic activity. The Quitzocho ridge from the base of the cone to the right. Note small pond formed by a lava dam. Photograph taken from the northeast.



NORTH FLANK CHIMNEY AND HEAVY EXPLOSIONS WITH LARGE BOMBS

A.—Early July. Chimney on the north flank of the cone on the site of one of the eruptive vents of June, after the cone had been restored by uninterrupted ash fall. Lava of June on ash-covered lavas of the Quitzocho flow. View from Cerro de Jarátiro. Photograph by Ezequiel Ordóñez.

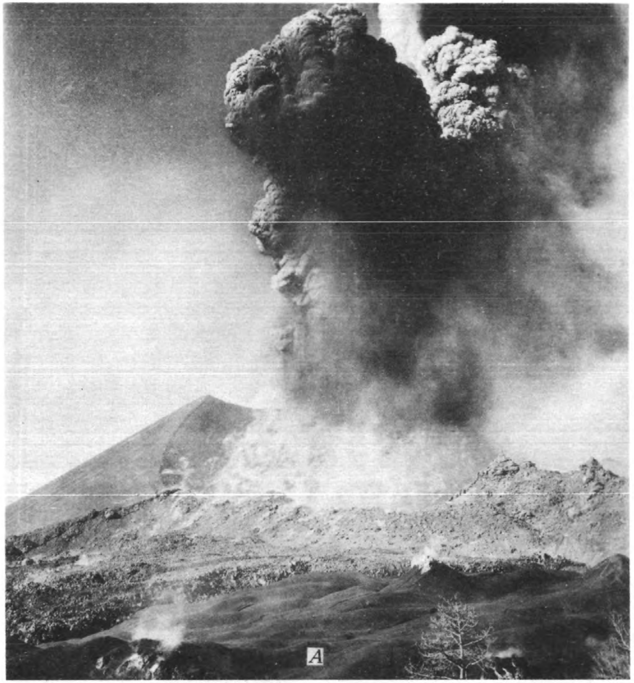
B.—July 31, 1943. Heavy explosions with large bombs and moderate vaporous eruptive column. The break of the cone of early July now largely restored. An old crater of Cerro de Jarátiro in the foreground. Photograph taken from Cerro de Jarátiro.

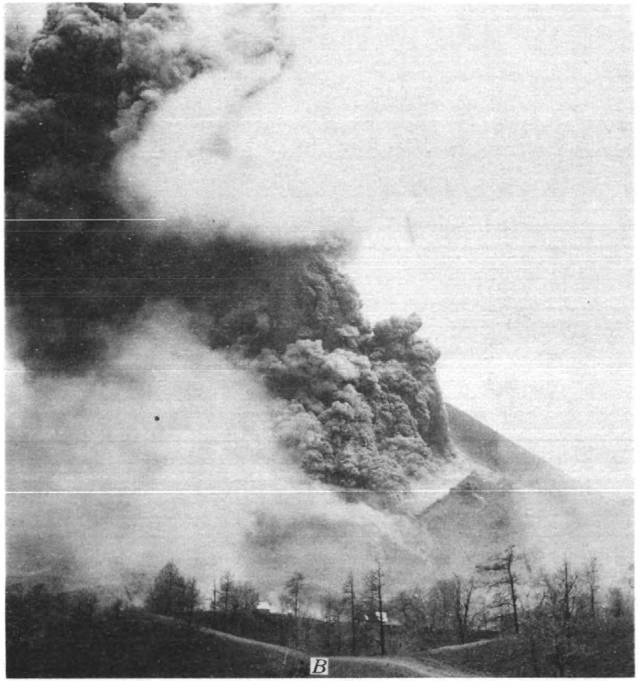


LAVA BUBBLES BURSTING IN CRATER

A.—August 1, 1943. Tremendous bursts of huge lava bubbles in crater, accompanied by flashing arcs, yielding huge tatters of viscous lava. Photograph taken from Cerro de Jarátiro.

B.—Same as above; time exposure about 15 seconds. Ejected masses of viscous lava flow down the slopes of the cone. Dark area in upper center is a weak eruptive column.

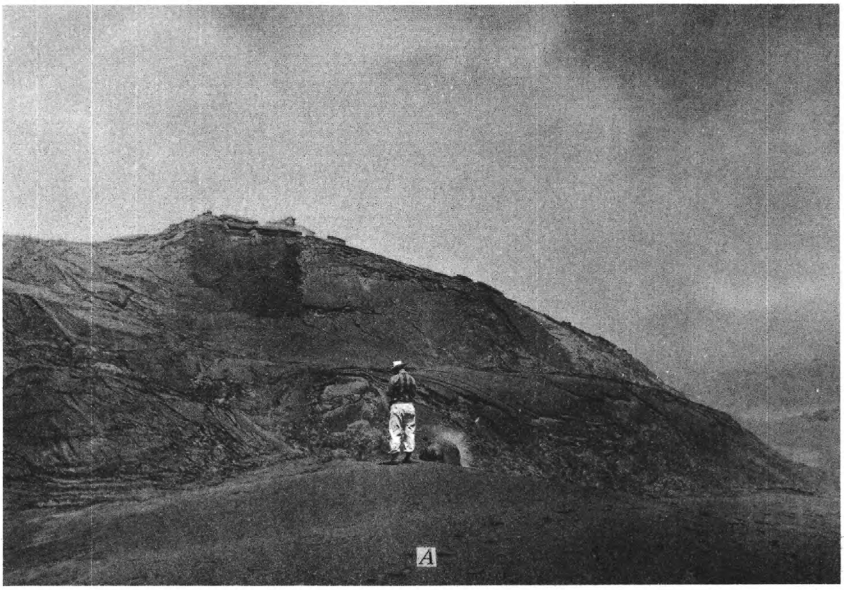




BREAKS IN THE CONE

A.—July 26, 1943. Cone viewed from Cerro de Jarátiro after the break in late July. Tremendous explosion from the north crater vent and heavy emission from south vent. Quitzocho ridge in the middle ground; ash-covered Quitzocho lava with salt-incrusted fumaroles in foreground.

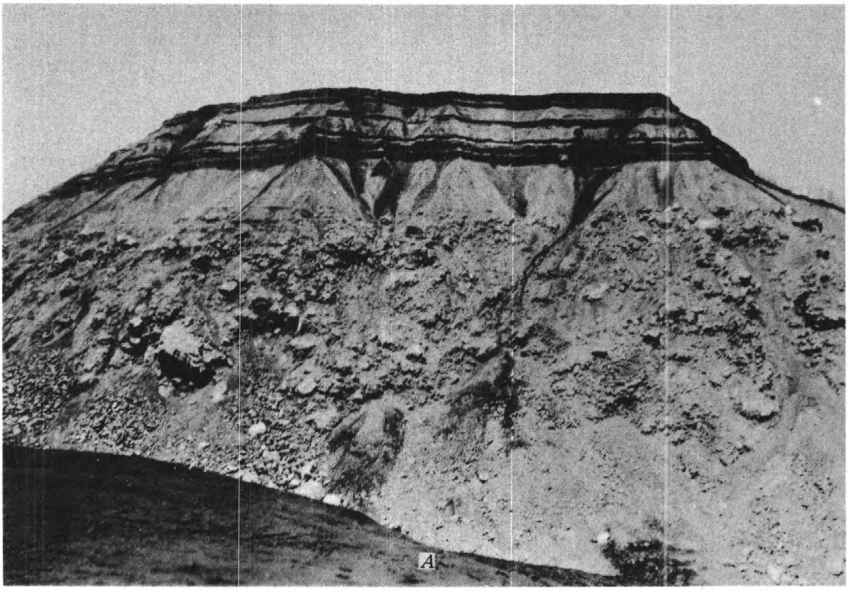
B.—August 2, 1943. The break in the cone in early afternoon. Huge jets of black ash play from the broken segment of the cone. The rocks, "Los Faroles," that crown the ridge are beginning to move to the left. One of the craters of Cerro de Jarátiro is in the foreground. Photograph taken from Cerro de Jarátiro.

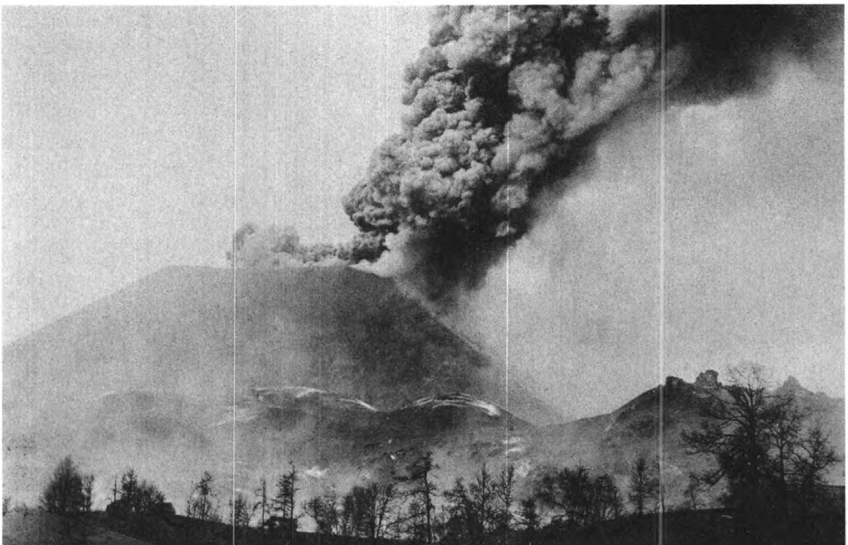


EARLY AND LATE STAGES OF QUITZOCHO RIDGE GROWTH

A.—June 10, 1943. Early stage in the growth of Quitzocho ridge by injection of lava below the ash during the lava outbreak of June 10.

B.—August 25, 1943. Late stage in the growth of Quitzocho ridge. The large blocks at the ridge terminus are of disintegrating lava. The dust, left center, is from boulders displaced by the elevation of the ridge. The foot of Cerro de Jarátiro is to the left. Photograph by Ezequiel Ordóñez.





QUITZOCHO RIDGE

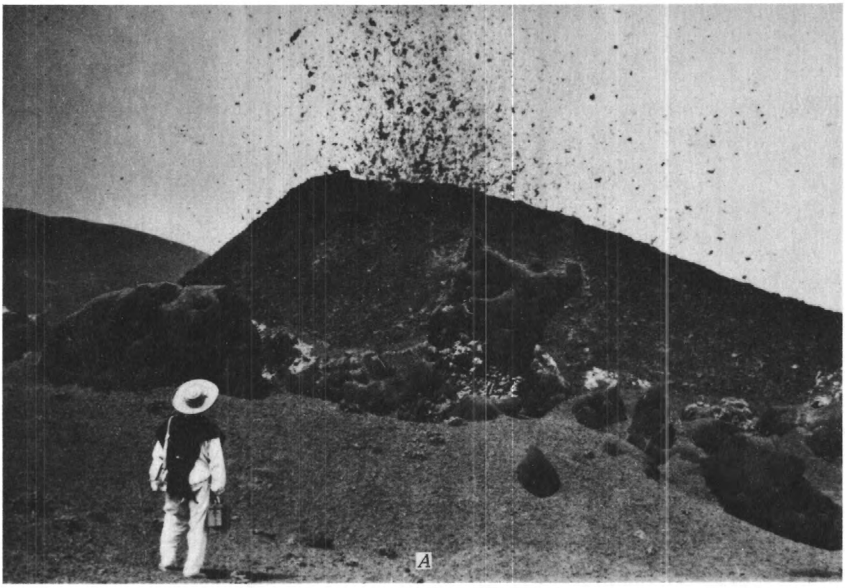
A.—September 1943. Portion of Quitzocho ridge showing elevated stratified ash on top and disintegrated lava below. Photograph by Ezequiel Ordóñez.

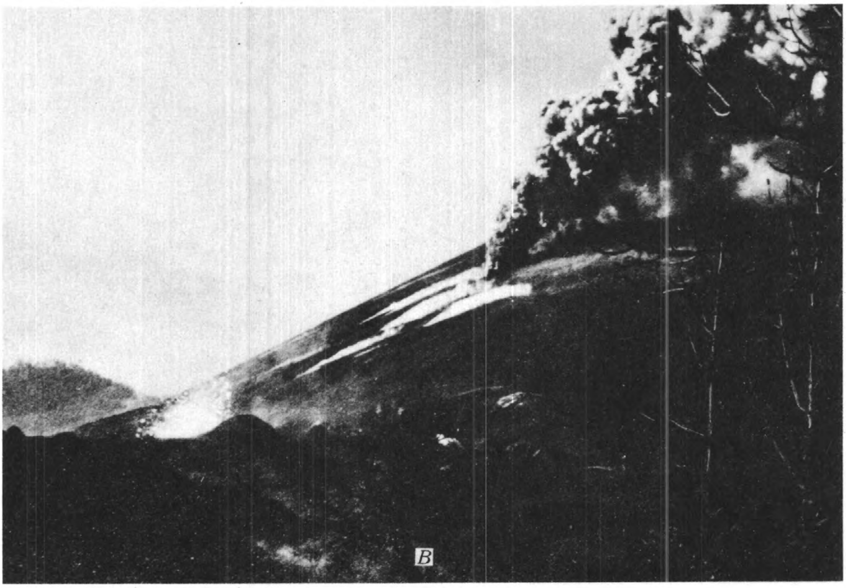
B.—September 17, 1943. Lazy emission of ash-laden eruptive column. On the right is part of the Quitzocho ridge with "Los Faroles" at the right. Old crater of Cerro de Jarátiro in foreground.

STEAMING ASH IN UPPER LEVELS OF CONE AND OUTBREAK OF SAPICHU AT BASE OF MAIN CONE

A.—October 19, 1943. Zone of steaming ash in upper levels of the cone. Such sharply defined haloes of steam were fairly common. Taken from the summit of Cerro de Jarátiro. Photograph by Arno Brehme.

B.—October 20, 1943. Outbreak of Sapichu viewed from the east. A series of vents extending from base of main cone to northeast broke out in the old Lagunita flow. Photograph by Lyn Storm.

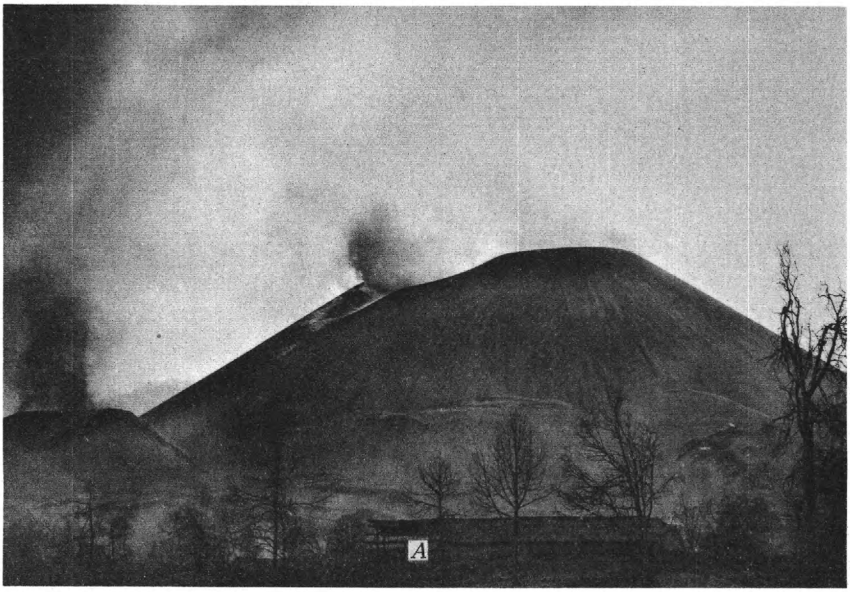


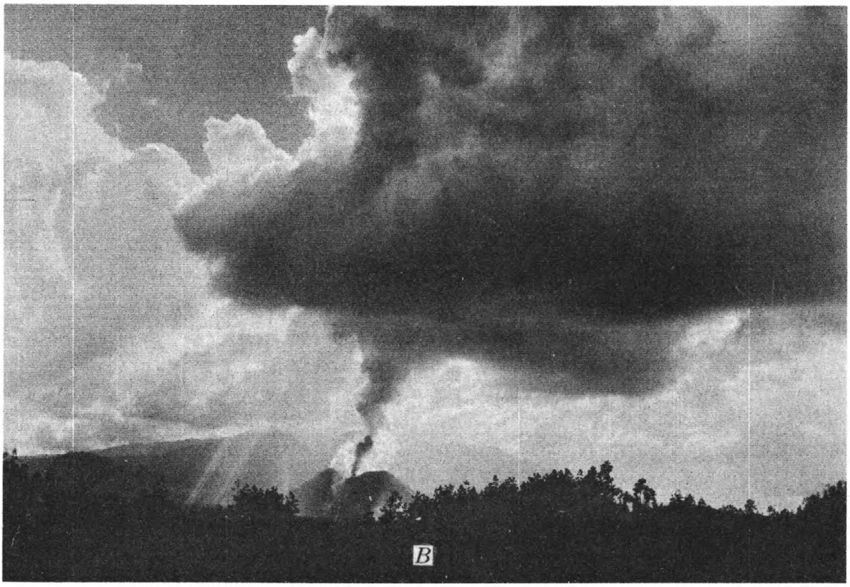


SAPICHU

A.—October 21, 1943. The new adventitious cone, Sapichu, at the base of Parícutin. A continuous fountain of viscous bombs without visible eruptive column. Taken from the east. Photograph by Lyn Storm.

B.—October 21, 1943. Eruptive chimney and steaming cracks on the north slope of Parícutin, and the new cone of Sapichu at the base of the cone. Taken from the northwest. Photograph with infrared film by Lyn Storm.





SAPICHU ERUPTING

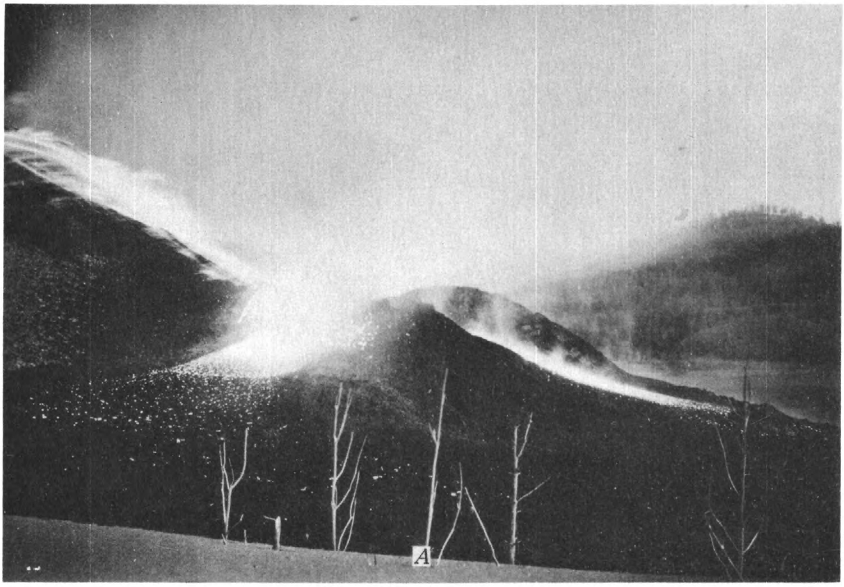
A.—November 28, 1943. During eruption of Sapichu, activity in the Parícutin crater was reduced to a lazy emission of vapor. A depressed boggy swale extended from the summit toward Sapichu, and the north slope was crusted with salts. Photograph taken from Cerro de Jarátiro.

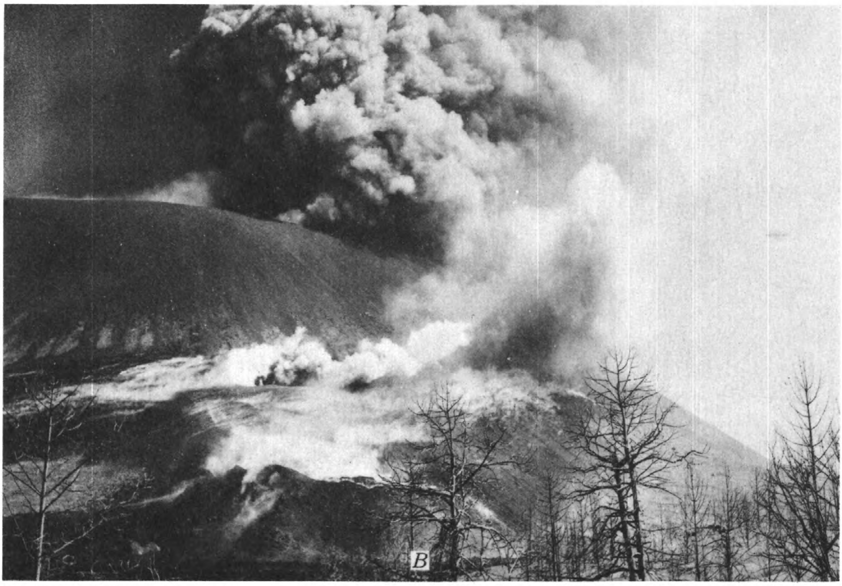
B.—December 6, 1943. The vaporous emission from Sapichu sometimes condensed as a huge cloud above the volcano. Cumulus clouds in background. Photograph taken from Angahuan.

ASH-COVERED HILLS AND FLOWS

A.—January 9, 1944. Lower slopes of Cerro de Canicjuata on the left; ash-covered Quitzocho ridge in the distance. Photograph taken from the southwest.

B.—January 8, 1944. Fissures and displacement in ash along a "tremor zone" at the foot of Mesa de Cocjarao, west of the cone.

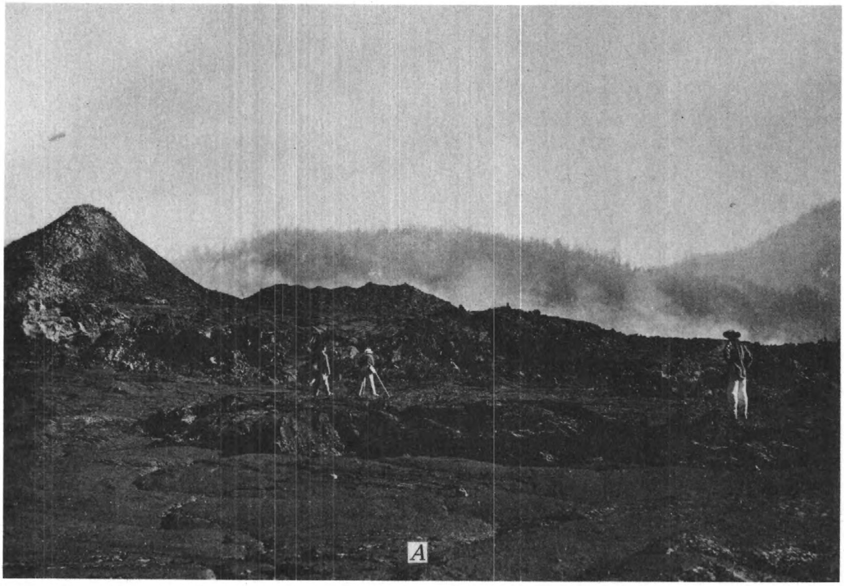


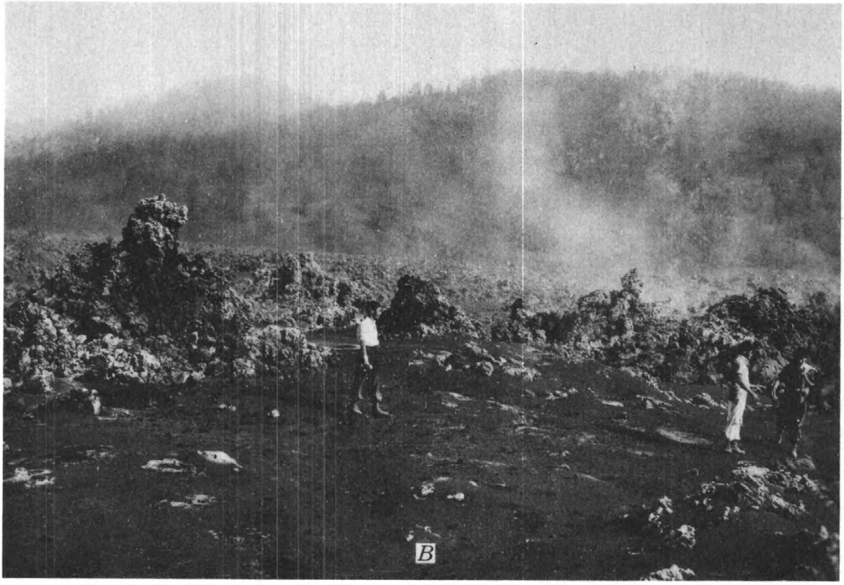


TAQUÍ VENTS

A.—January 8, 1944. First day of the Taquí lava flow. Three vents yielded a continuous flow of lava. Steaming lower slopes of the cone to the upper left; lower slopes of Cerro de Canicjuata in the foreground. The varying degrees of incandescence mark lava surges. Photograph taken from the northwest.

B.—January 9, 1944. Area of the Taquí vents, which are on the lower slope, an eruptive chimney upon an upper knoll. Taquí lava flow on the lower left; slopes of Mesa de Cocjarao lower right.

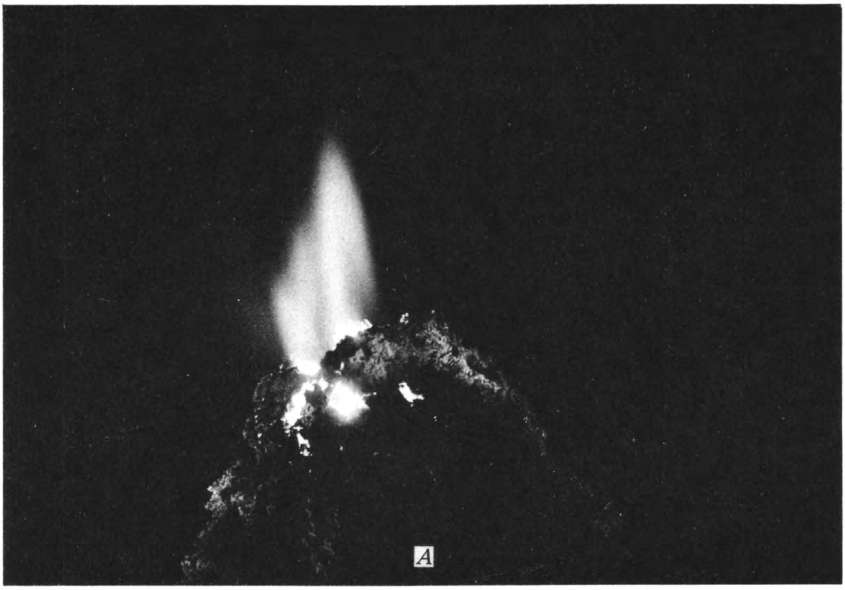


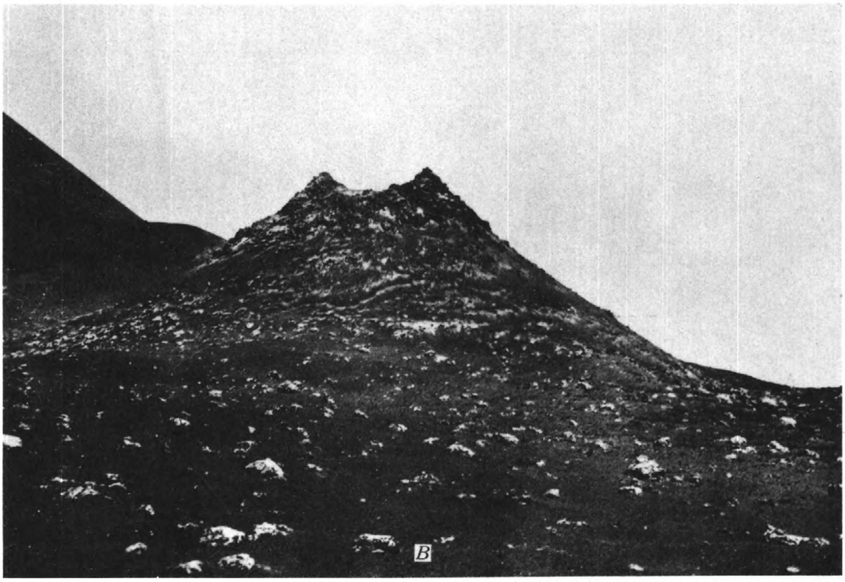


MESA DE LOS HORNITOS

A.—March 21, 1944. Area of the Taquí vents (now buried), now called Mesa de Los Hornitos. Pahoehoe lava from "volcancito" to the left. Photograph taken from the north.

B.—May 24, 1944. Surface of the Taquí lava flow showing the hornito fields. Abundant yellow and orange salts colored the area, Mesa de Los Hornitos. Photograph taken from the northeast.

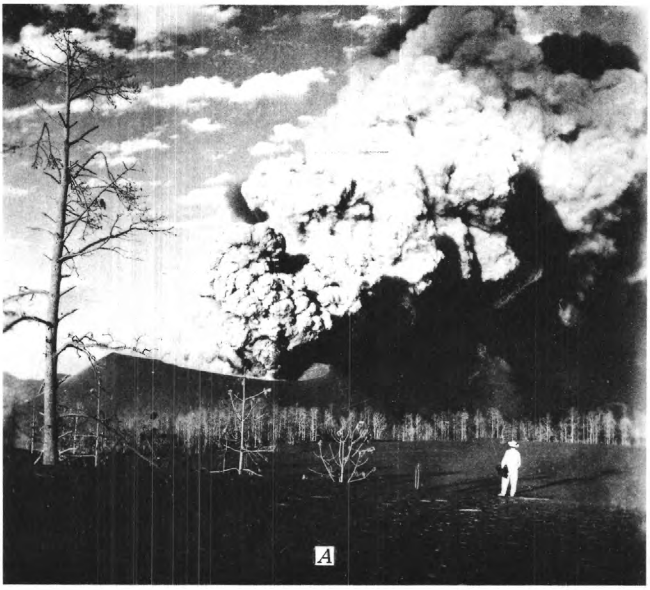


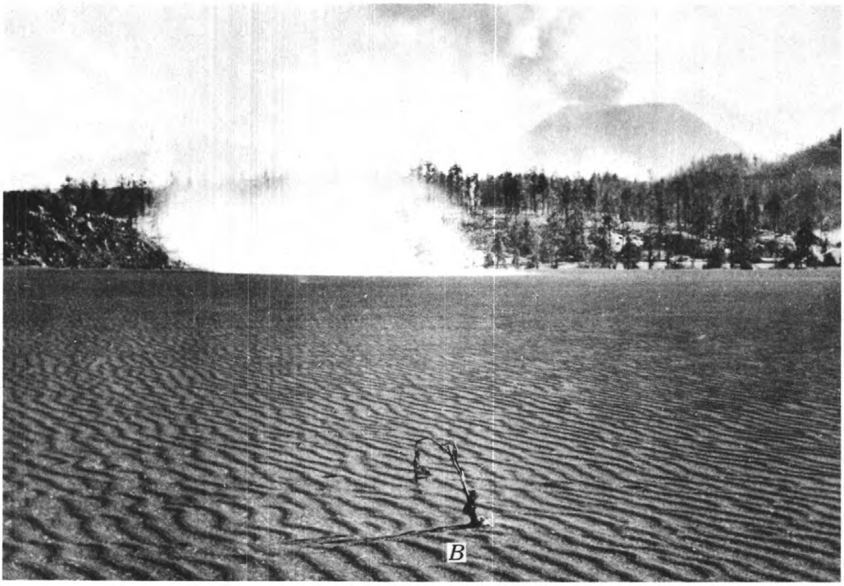


A HORNITO AND A VOLCANCITO

A.—March 22, 1944. Burning gases from the orifices of a hornito. These flames are pale blue and only visible at dusk and night. The vents are lined with fused lava.

B.—May 24, 1944. A volcancito on the surface of the Taquí lava flow. Such edifices eject small bombs and emit burning gases and bluish fumes from their summit vents. They are situated above the area of the Taquí vents and are due to a flow of gas-charged lava through cracks in the lava crust. Photograph by Ezequiel Ordóñez.

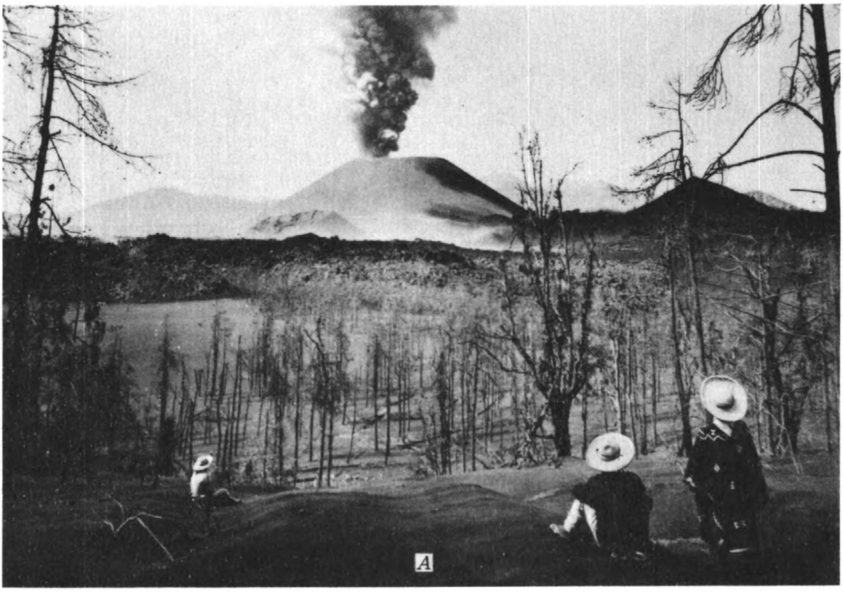




PARÍCUTIN VOLCANO

A.—March 22, 1944. Parícutin volcano from Mesa de Cocjarao. The lowered south rim is due to scouring by the eruptive column of the south crater vent. Eruptive column is pale buff and largely vaporous. Photograph taken from the southwest.

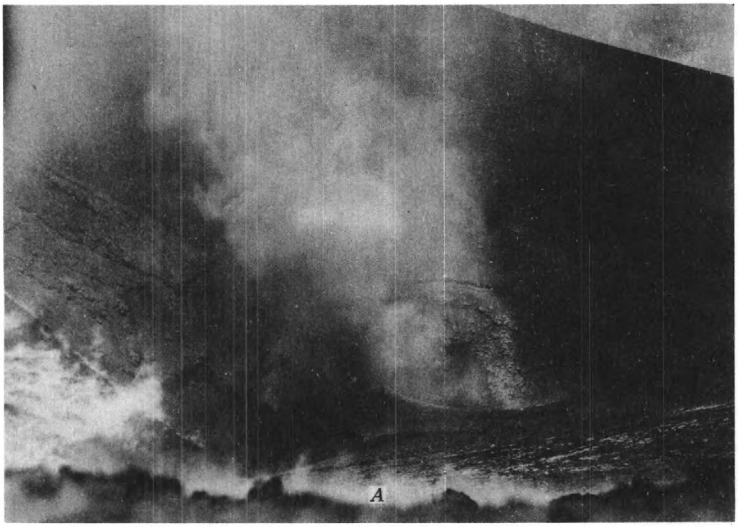
B.—March 1944. Parícutin volcano looking northeast from Las Cruces. Wind-blown ash in the foreground. Photograph by Arno Brehme.

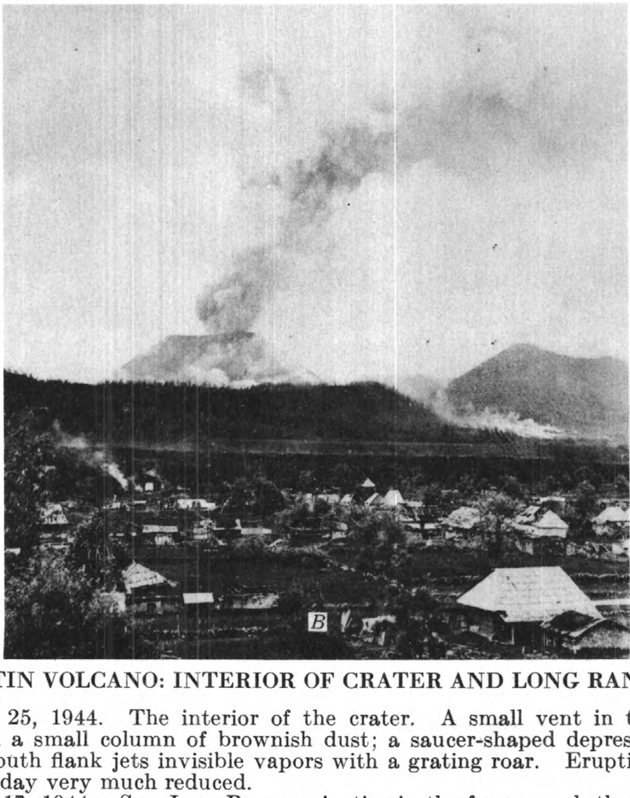


PARÍCUTIN VOLCANO FROM CERRO DE EQUIJUATA AND CERRO DE JARÁTIRO

A.—March 1944. Parícutin volcano from northeast at Cerro de Equijuata. Sapichu at the foot of main cone. Rugged lava of the flows of June in the middle distance. Photograph by Arno Brehme.

B.—May 27, 1944. Parícutin emitting sparse ash—vapors are also being emitted, but they cannot be seen. This type of activity is accompanied by an intermittent rolling rumble and fall of gritty ash. Photograph taken from Cerro de Jarátiro.

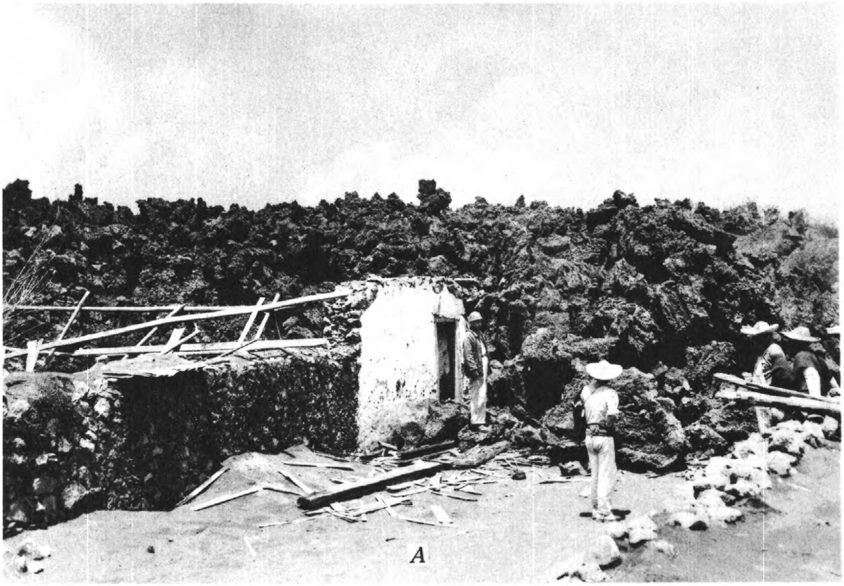


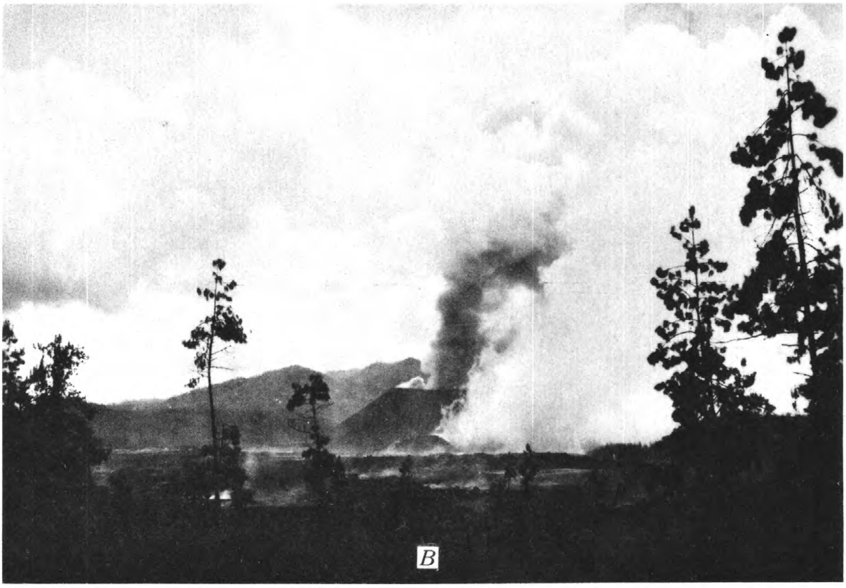


PARÍCUTIN VOLCANO: INTERIOR OF CRATER AND LONG RANGE VIEW

A.—May 25, 1944. The interior of the crater. A small vent in the bottom emitted a small column of brownish dust; a saucer-shaped depression in the lower south flank jets invisible vapors with a grating roar. Eruptive activity on this day very much reduced.

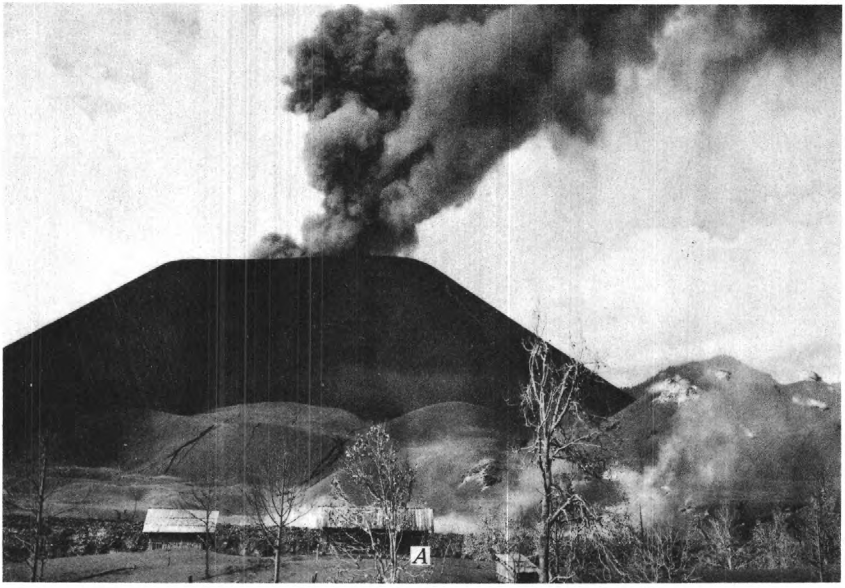
B.—June 17, 1944. San Juan Parangaricutiro in the foreground, the Parangaricutiro lava tongue beyond; Parícutin lava flow (middle) steaming from recent rain. Cerro de Canicjuata on right; Cerro de Jarátiro on left. Photograph taken from Cerro de La Capilla, north.

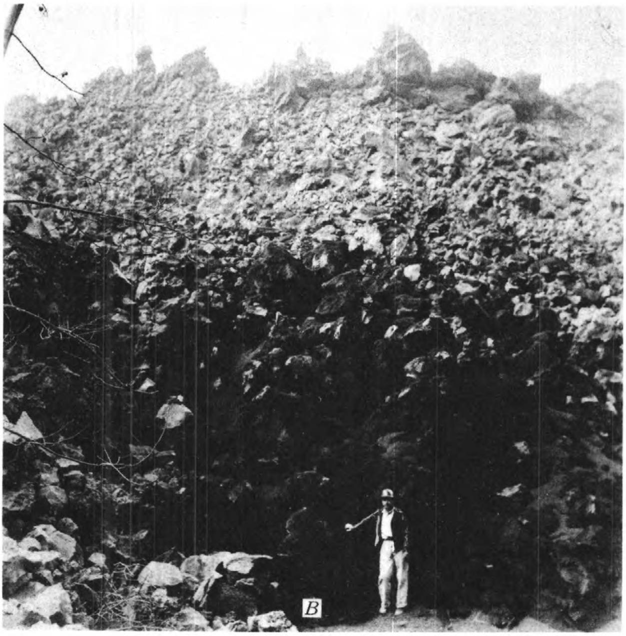

A


B

PARANGARICUTIRO TONGUE AND PARÍCUTIN VOLCANO

A.—June 20, 1944. Parangaricutiro lava tongue advancing slowly through the town.
B.—August 14, 1944. Fog drifting in from the west is halted by the rising eruptive column of Parícutin. Photograph taken from Cerro de Nureto, northeast.

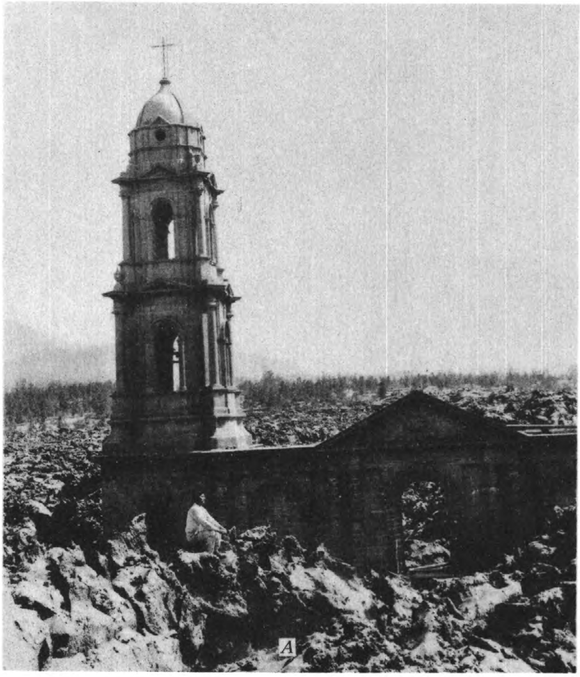


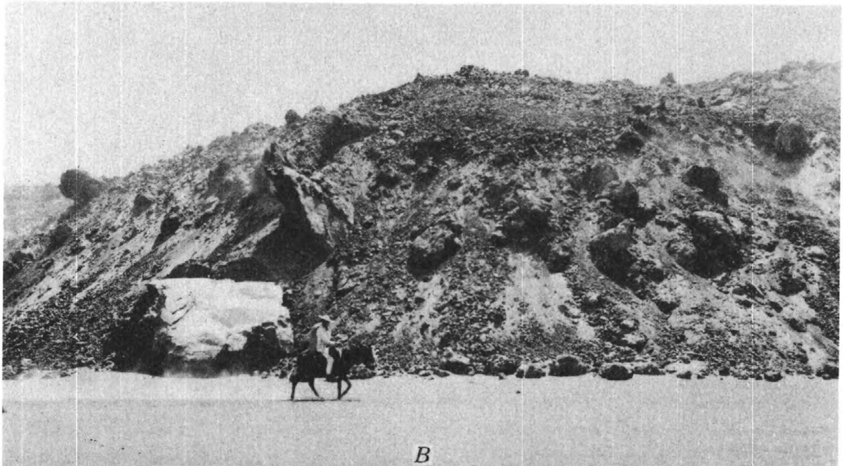


ERUPTIVE COLUMN AND BLOCK LAVA FRONT

A.—August 16, 1944. Characteristic eruptive column during this period. Quitzocho ridge to the right. Campamento tongue of the Taquí flow behind the houses. Photograph taken from Cerro de Jarátiro.

B.—July 31, 1944. Block lava front from a small flow from Quitzocho ridge.

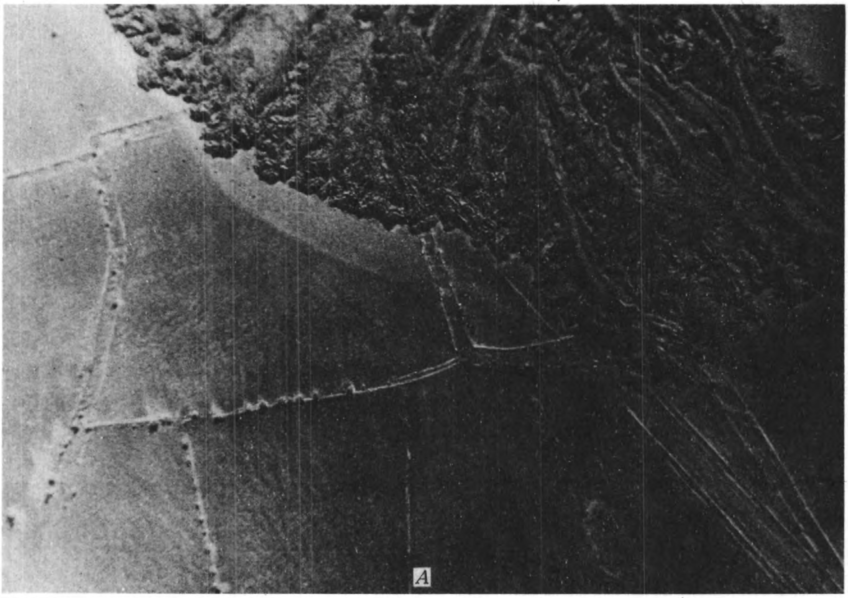


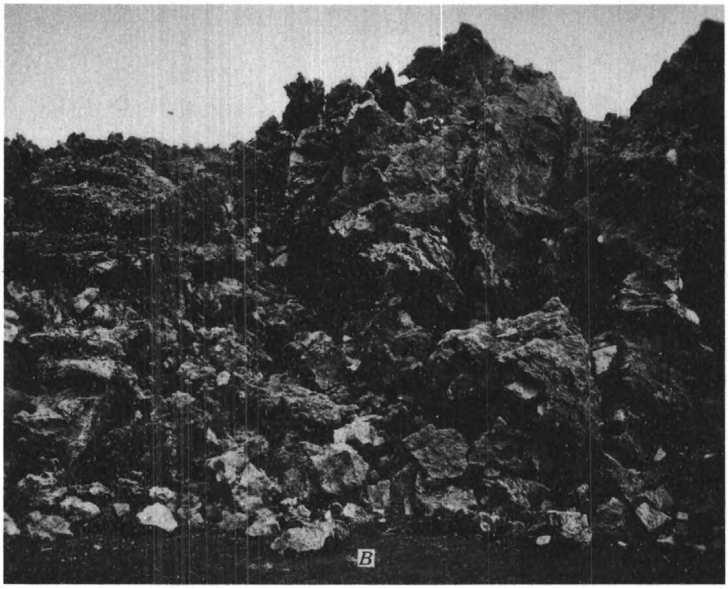


PARANGARICUTIRO TONGUE AND SAPICHU FLOW

A.—January 25, 1945. The tower of the San Juan Parangaricutiro church above the lava of the Parangaricutiro tongue of the Taquí flows. Behind the tower lies the engulfed town.

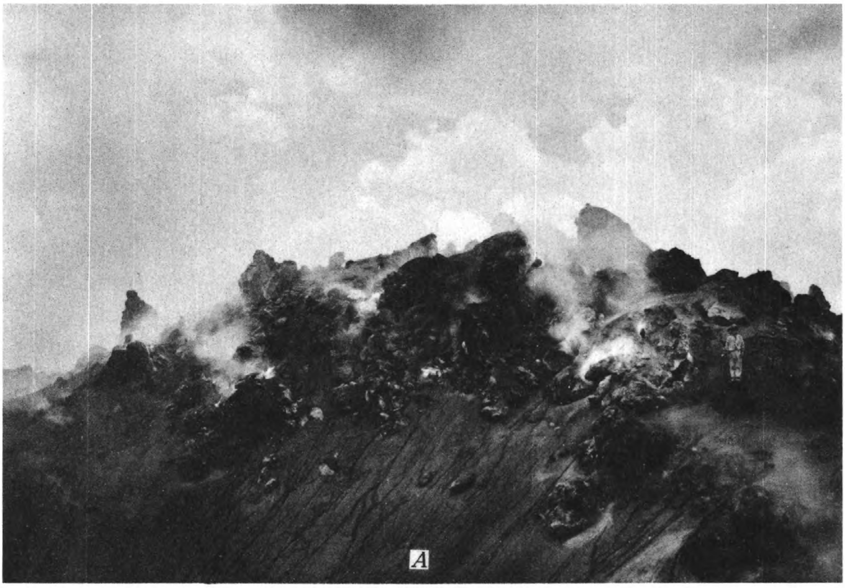
B.—March 23, 1944. The rubble front of the Sapichu lava flow at the San Juan Parangaricutiro–Uruapan road. A common type of lava at Parícutin.





PARANGARICUTIRO TONGUE: AERIAL AND GROUND VIEWS

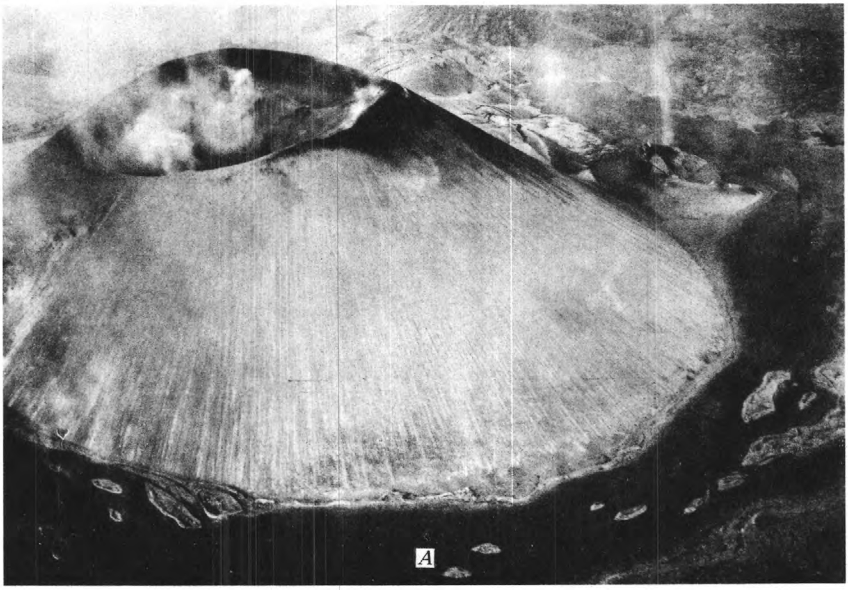
A.—December 2, 1944. Aerial view, end of the Parangaricutiro lava flow at Llano de Huirambosta, showing the individual lava emissions from the top of the lava flow, a feature peculiar to this tongue. Photograph by Otto O. Fisher.
B.—July 1, 1944. Structure of the Parangaricutiro tongue of the Taquí flows. This torn structure is peculiar to this tongue.

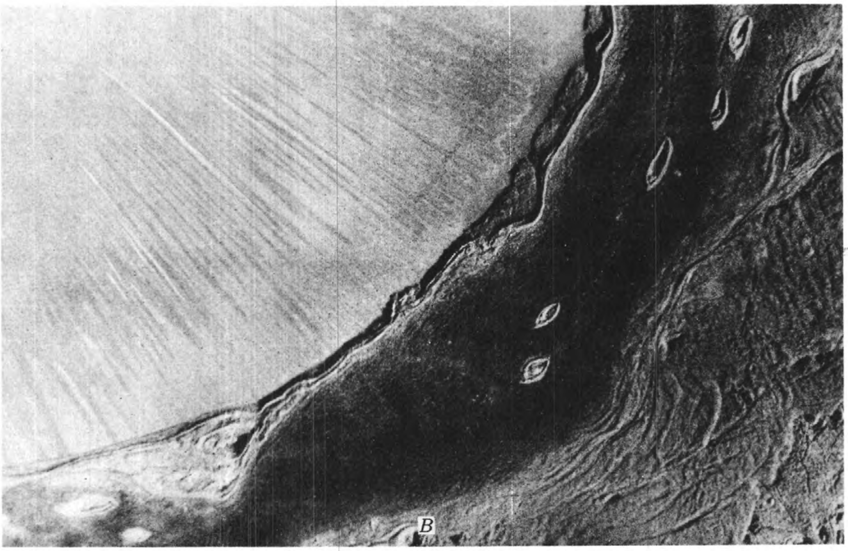


SAPICHU AND TAQUÍ FLOWS

A.—August 17, 1944. Fumaroles in the Sapichu flow, with deposits of yellow and orange iron and aluminum chlorides.

B.—Mid-November 1944. The Ahuán break and beginning of the Ahuán flows, viewed from the south. In the foreground lavas of the Taquí flows. Fresh lava photographs black. Aerial photograph by Frank Zierer.

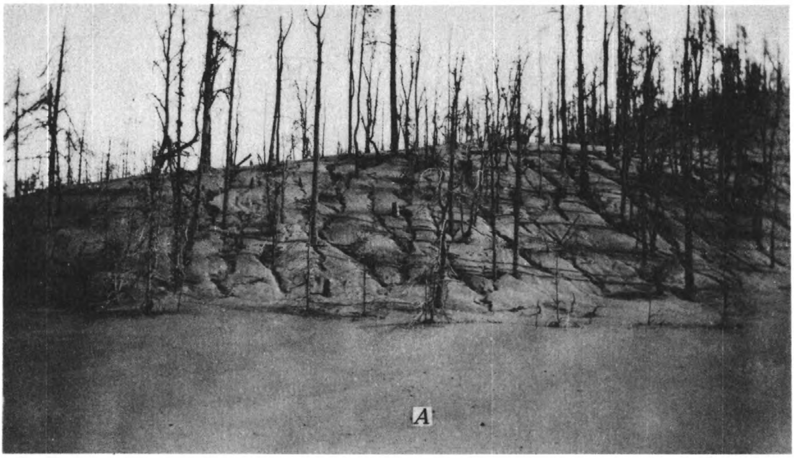


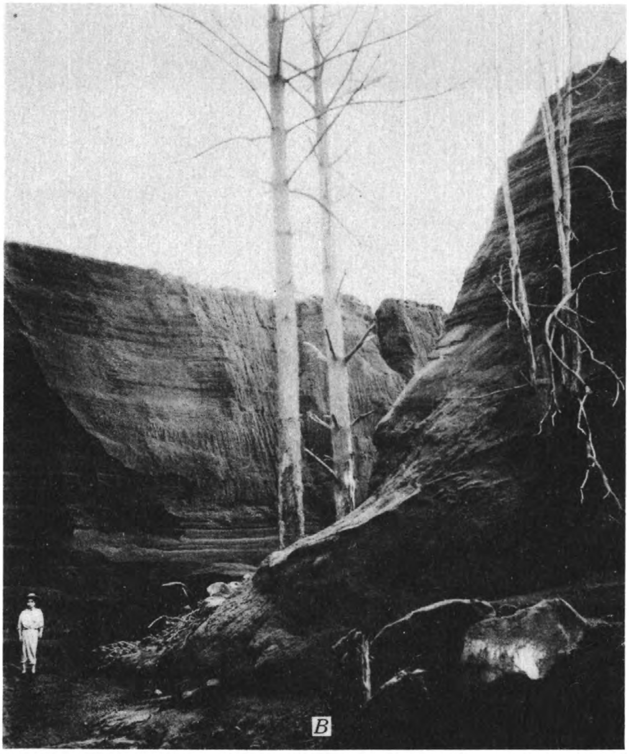


AHUÁN FLOW

A.—November 29, 1944. The cone and crater and the Ahuán flow viewed from the south. Sapichu at opposite base of the cone. Aerial photograph by Otto O. Fisher.

B.—December 2, 1944. Details of the Ahuán flow showing kipukas of Taquí lava, clinker dikes of the flow along the base of the cone, and overflow of the lava to the right. Photograph by Otto O. Fisher.

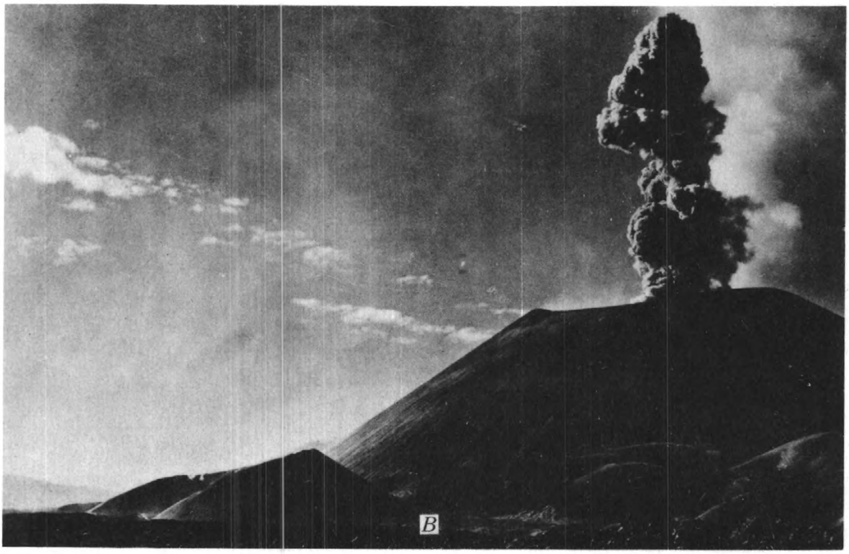




TYPICAL EROSION IN ASH

A.—January 25, 1945. Typical erosion gullies in the ash. A mat of pine needles from the dead trees frequently inhibits erosion. Photograph by Ezequiel Ordóñez.

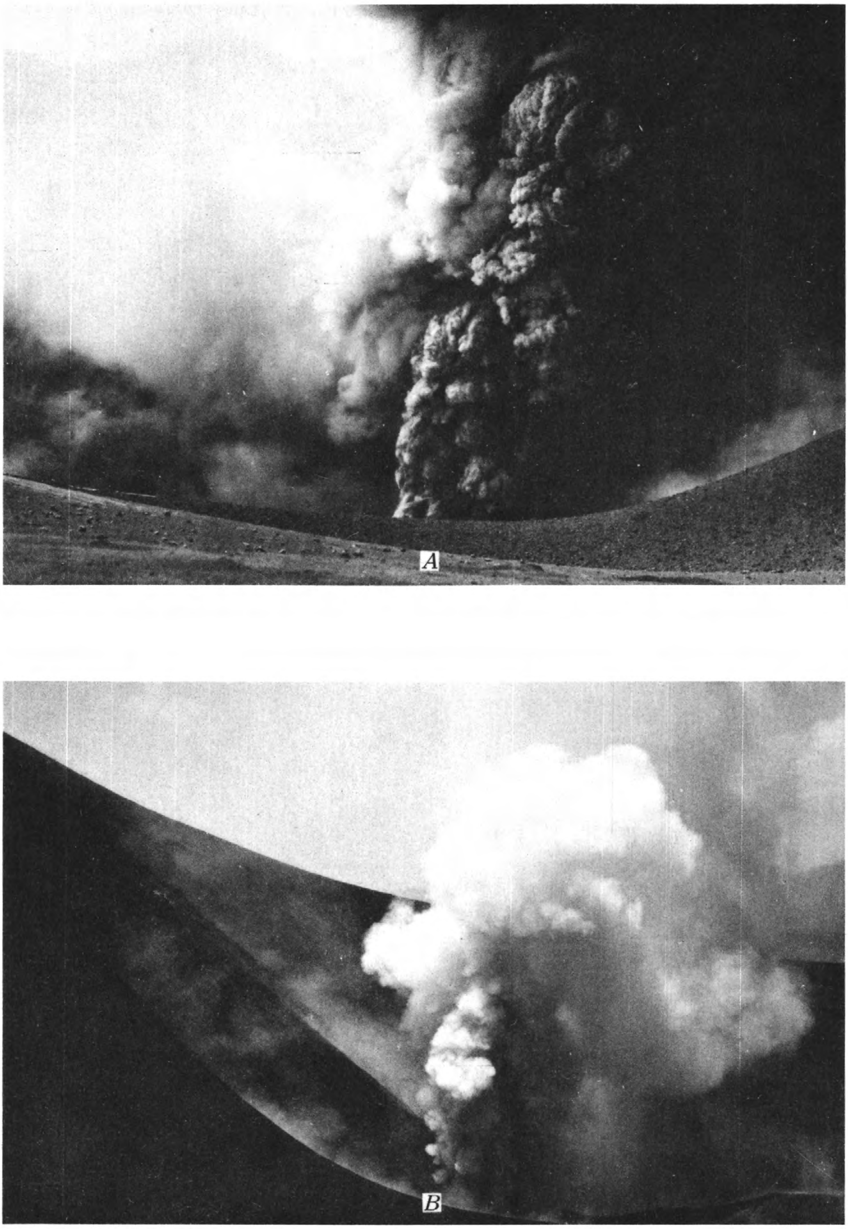
B.—Erosion arroyo in the ash at the foot of Cerro de Canicjuata, the result of a single storm. Erosion has taken place several feet below the old land surface.



CRATER EMISSIONS

A.—December 4, 1944. Weak vaporous crater emission with a little gritty ash. This type of explosion is accompanied by a rolling rumble. Photograph taken from Cerro de Jarátiro.

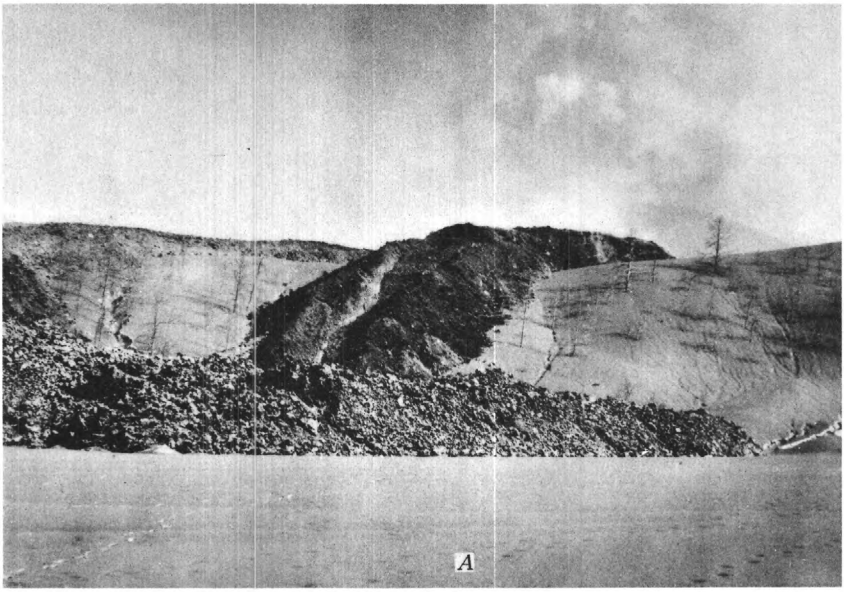
B.—December 6, 1944. One of the intermittent crater explosions that were followed by a period of quiet. Photograph taken from Cerro de Jarátiro.

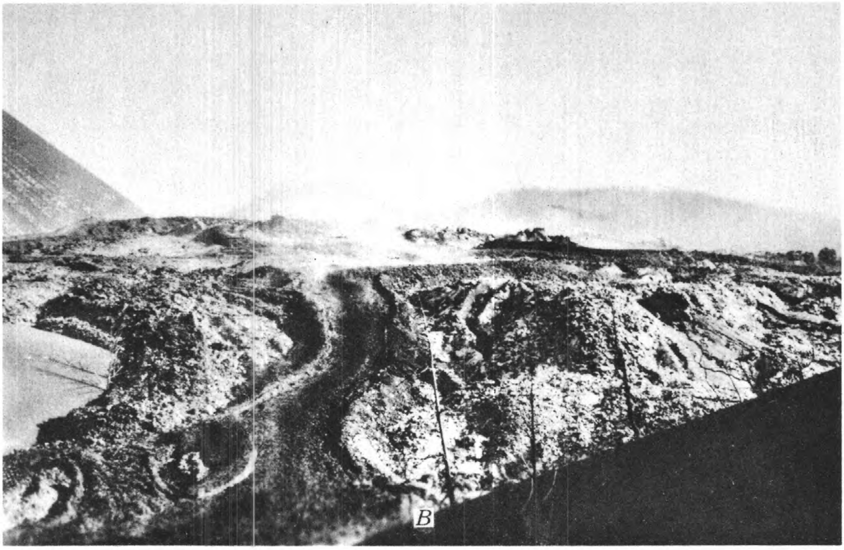


INTERIOR OF THE CRATER

A.—January 23, 1945. Interior of the crater, with one eruptive vent and a medium-sized eruptive column charged with ash.

B.—May 27, 1945. Interior of crater with two vents; the north vent emits a continuous column of white vapors; the south vent, beyond the low medial ridge, erupts at irregular intervals.

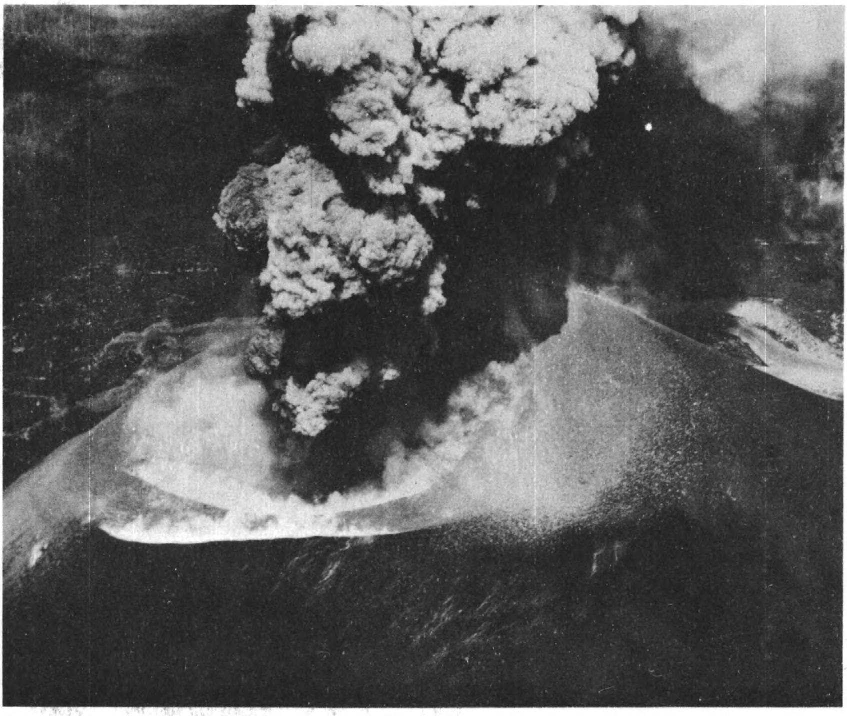




TAQUÍ FLOWS POURING OVER A RIDGE

A.—February 18, 1945. One of the Taquí flows pouring over a ridge. The fluid center of the flow has left a deep trench, but a second lava surge begins to fill it. Taken from the north. Photograph by Ezequiel Ordóñez.

B.—July 1945. Same area viewed from the north 5 months later, showing various flows. Mesa de Los Hornitos above. Photograph by Ezequiel Ordóñez.



INTERIOR OF CRATER

July 31, 1945. Interior of crater with one active vent. The bench is a remnant of a higher floor of the crater. Aerial photograph taken from the south.