Geologic Investigations in the Parícutin Area Mexico

UNITED STATES DEPARTMENT OF THE INTERIOR

Douglas McKay, *Secretary*

GEOLOGICAL SURVEY

W. E. Wrather, *Director*

CONTENTS

UNITED STATES DEPARTMENT OF THE INTERIOR

Oscar L. Chapman, *Secretary*

GEOLOGICAL SURVEY

W. E. Wrather, *Director*

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 ot 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.

1

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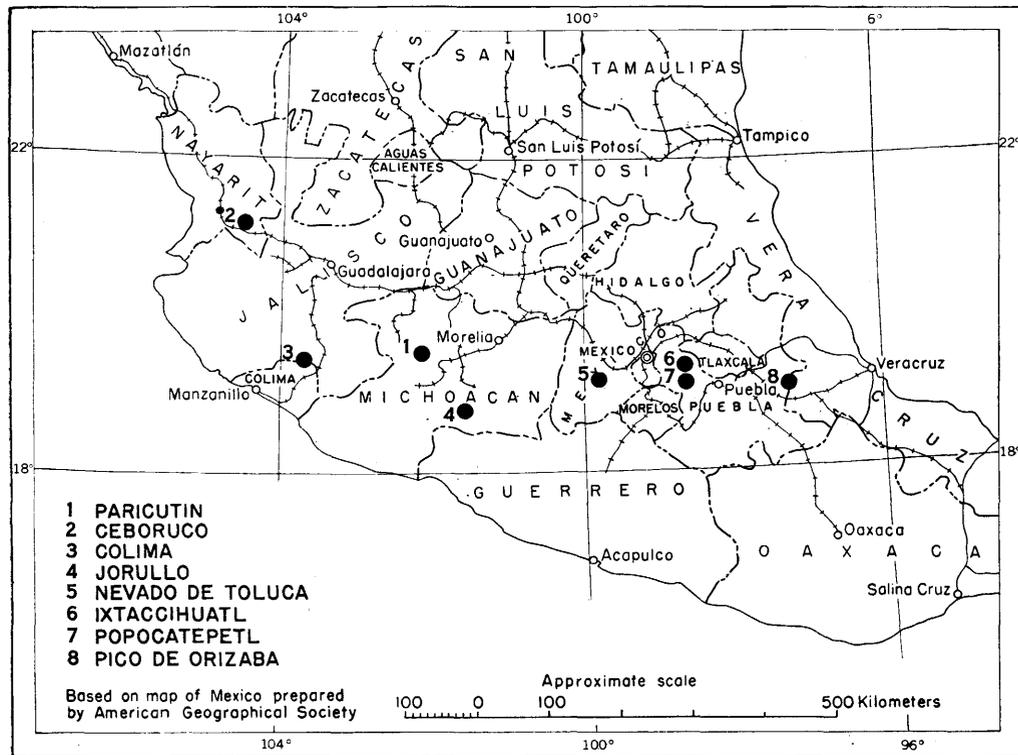
FIGURE 1.—Index map of southern Mexico, showing location of principal volcanoes.

Map legend:
1 PARICUTIN
2 CEBORUCO
3 COLIMA
4 JORULLO
5 NEVADO DE TOLUCA
6 IXTACCIHUATL
7 POPOCATEPETL
8 PICO DE ORIZABA

Based on map of Mexico prepared
by American Geographical Society

Approximate scale
100   0   100   500 Kilometers

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 observa-
tions 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

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.

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 Cuaxándaran 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 Paricutin 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 Paricutin 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 Paricutin 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 Paricutin 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 hori zontal 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)

VERTICAL SCALE
IN METERS

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

WEATHERED ZONE

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

WEATHERED ZONE

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

WEATHERED ZONE

UNCONFORMITY

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

WEATHERED ZONE

WEATHERED ZONE

Gray, coarse-grained. Contains some less coarse beds each about 5 cm.
  thick ---310

Brown soil-like horizon forming bench ---------------------------- 2½

WEATHERED ZONE

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

WEATHERED ZONE

WEATHERED ZONE

UNCONFORMITY

WEATHERED ZONE

NOTE
The vertical scale of the bottom 8 meters is distorted, but the total length of the column is in true scale

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), be-. tween 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 re-deposited 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
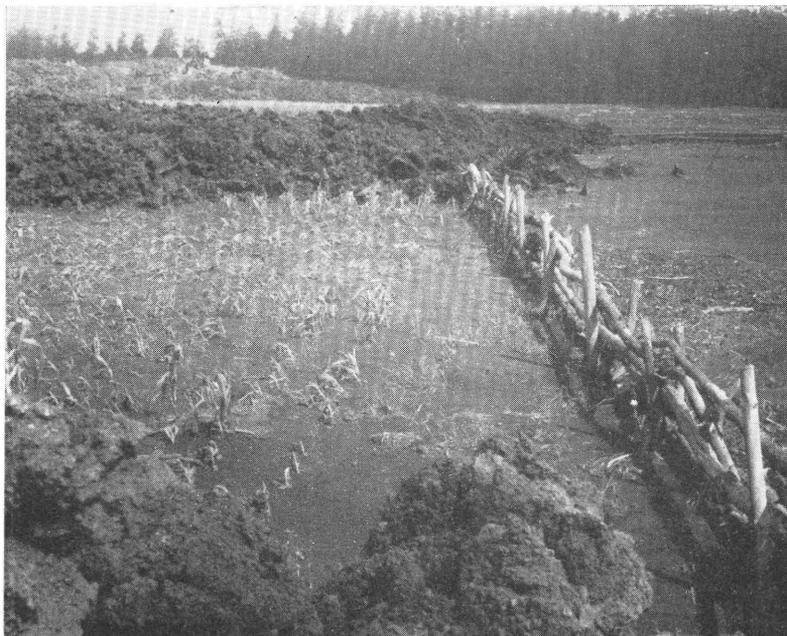
FIGURE 3.—Sowed on March 30, 1946, a cornfield at Chórotiro, near Parícutin, looked like this on August 6.

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 Paran-

garicutiro 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 inunda-

tion 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 non-

incandescent 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 ma-

terial 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)±	
850	Casita Canicjuata	1,100	256.7
1,500		600	77.0
1,700		500	50.0
2,000		400	33.3
2,600	Corucjuata triangulation station	300	16.7
3,600	Near Llano del Pueblo Viejo	200	10.0
5,800	Near Tiripan	100	4.5
8,000	Zirosto	50	2.3
10,500	Barranca Seca	25	1.0

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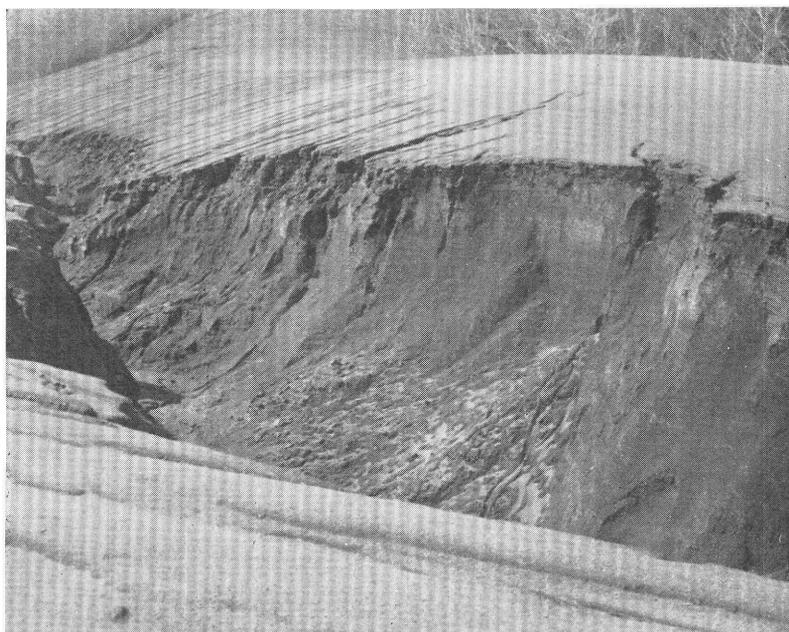
FIGURE 7.—New barranca eroded into the Casita Canicjuata ridge, near Parícutin, during a single storm.

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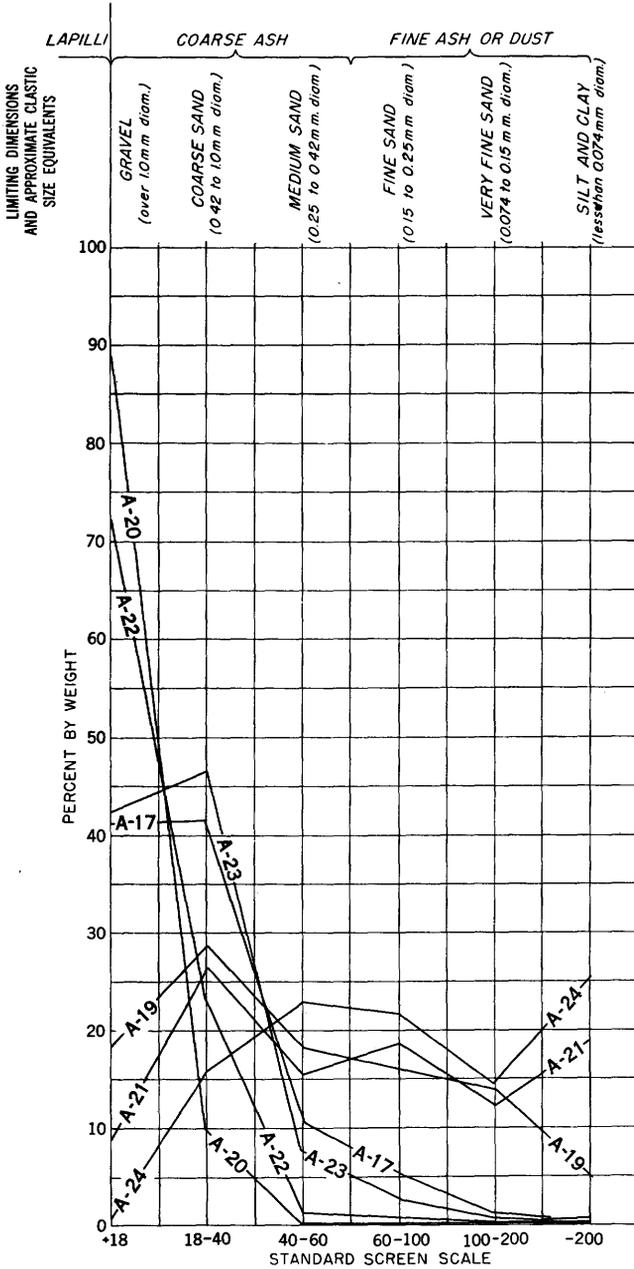
FIGURE 9.—Graph showing size distribution of particles in seven samples of ash from Parícutin taken from a pit at Jarátiro.

The bedding in the ash at Jarátiro 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
Cuaxándaran	158.0	15.5	2.5	66.5	2.0
Sinámichu	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
Jarátiro (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
Cuaxándaran	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.
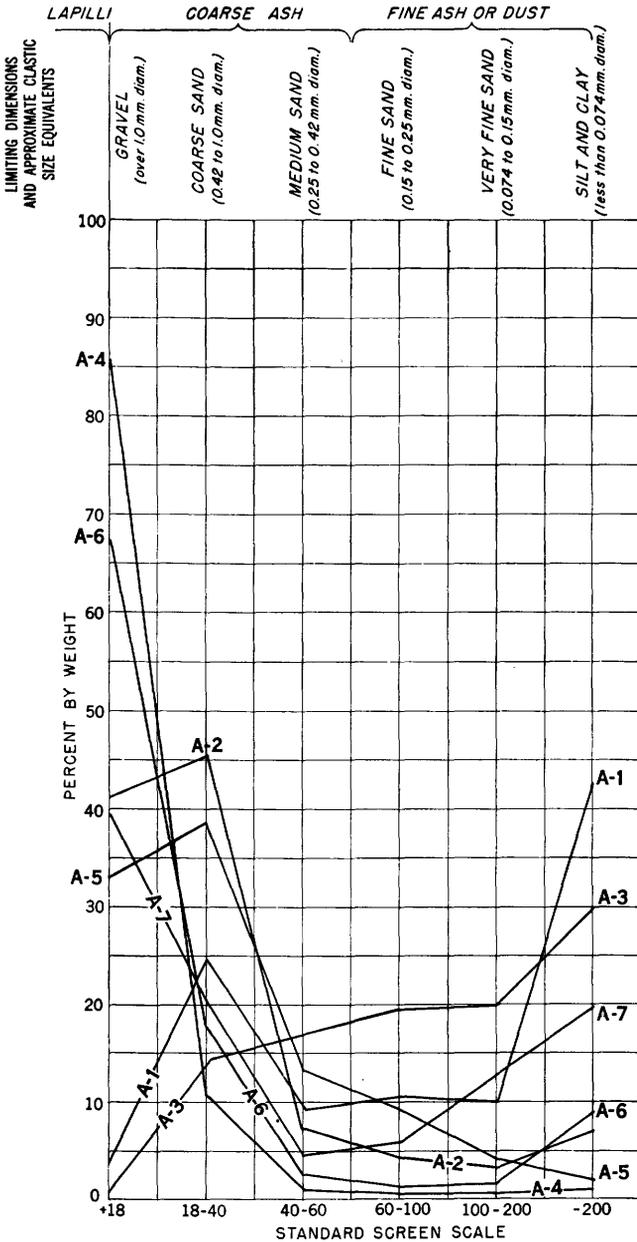
FIGURE 10.—Graph showing size distribution of particles in samples of ash from Parícutin taken from a pit on top of Cerro de Canicjuata.
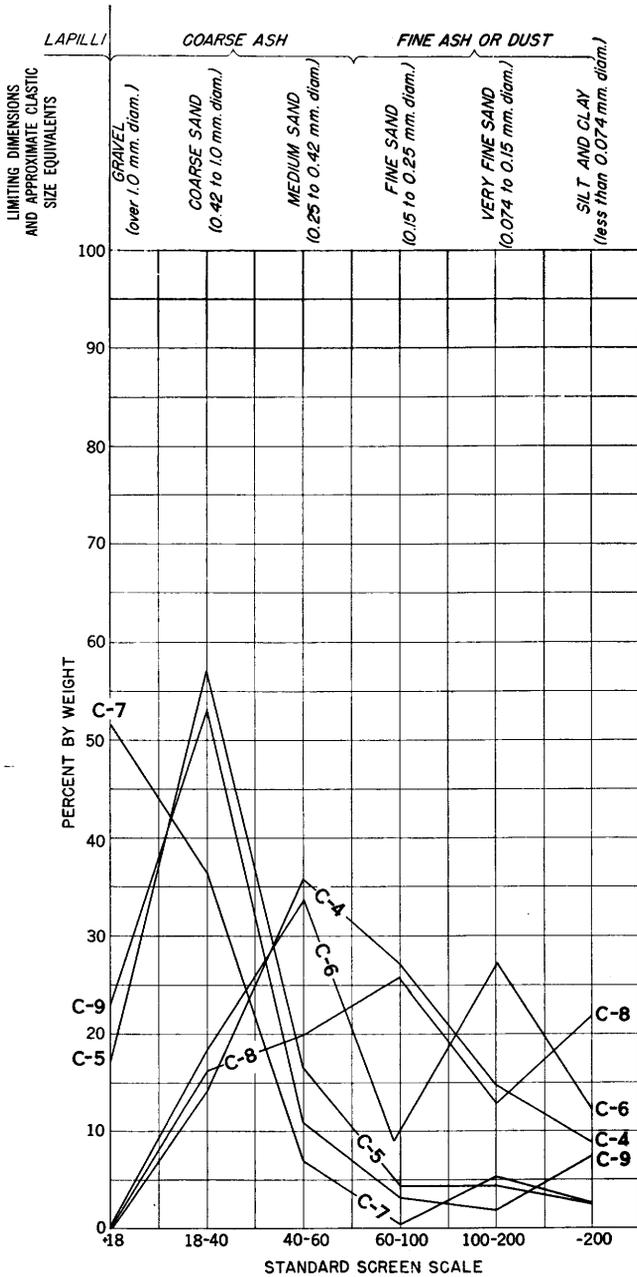
FIGURE 11.—Graph showing size distribution of particles in ash samples taken from various places southwest of the Parícutin cone.

TABLE 7.—*Particle sizes in coarsest- and finest-grained beds of ash from Paricutin 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 Paricutin 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 south-west.	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
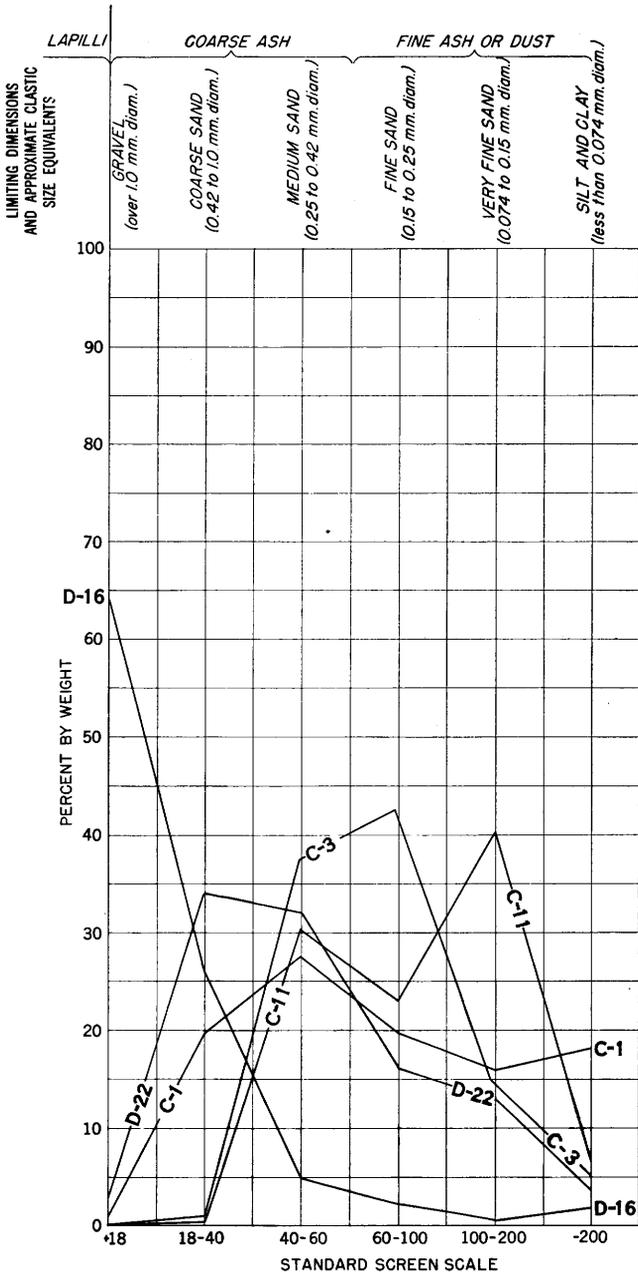
FIGURE 12.—Graph showing size distribution of particles in samples of fresh ash collected in the vicinity of Paricutin.
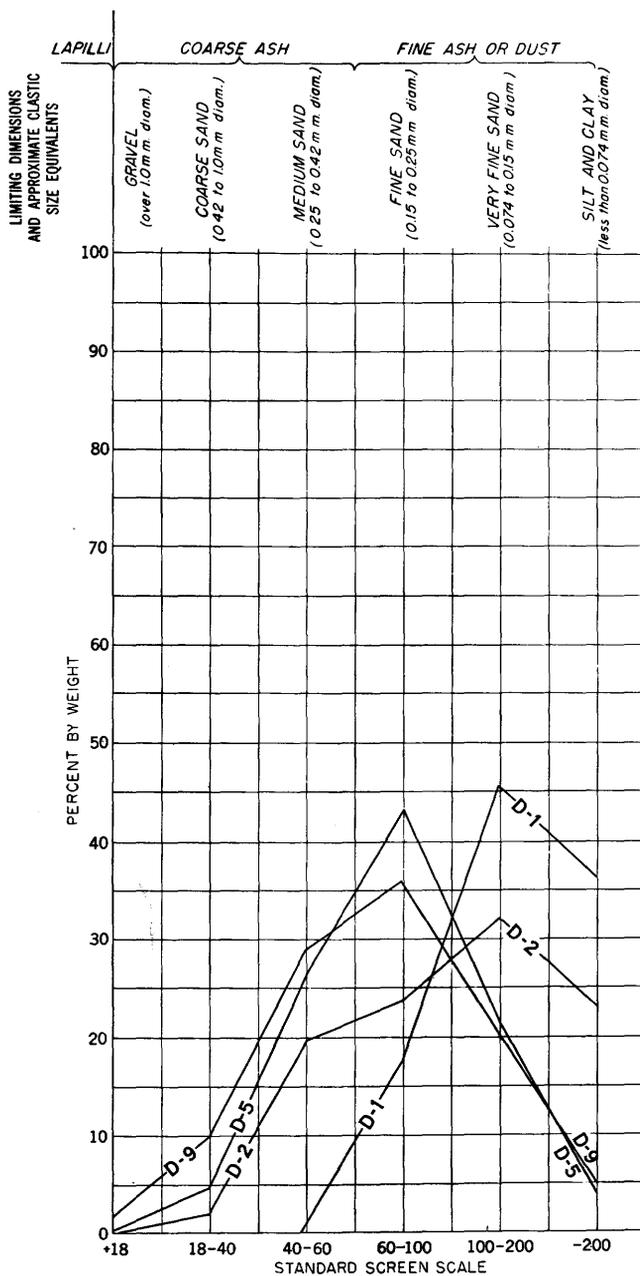
FIGURE 13.—Graph showing size distribution of particles in samples of newly fallen ash collected north and northwest of the Parícutin cone on October 11, 1946.
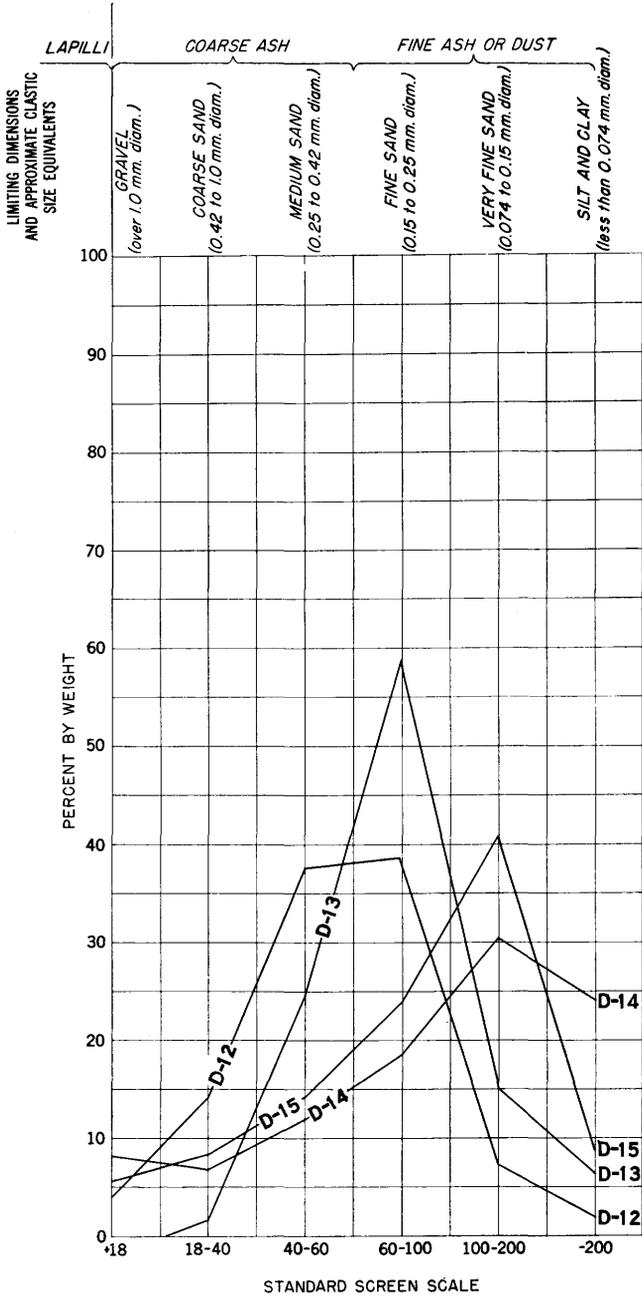
FIGURE 14.—Graph showing size distribution of particles in samples of newly fallen ash collected north and east of the Parícutin cone on October 11, 1946.

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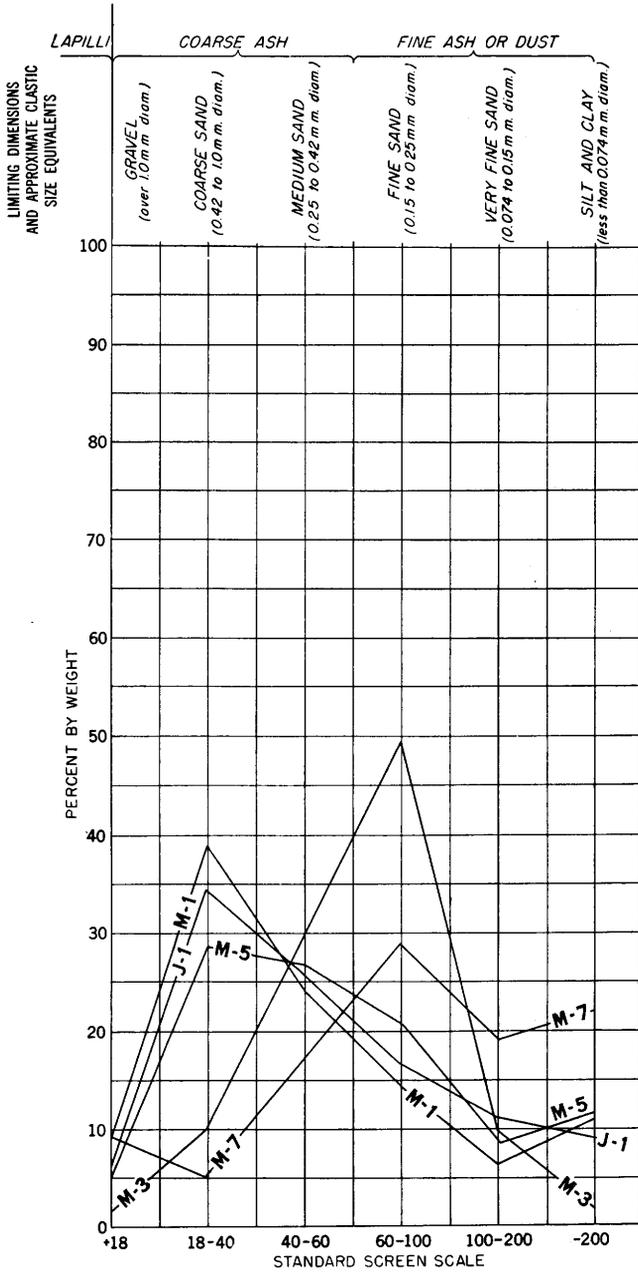
FIGURE 15.—Graph showing size distribution of particles in ash from Parícutin. Samples are from infiltration-test cores taken to a depth of half a meter from the surface.

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 com-
pactness 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, caus-
ing 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 perme-
able 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 pre-
cipitated 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
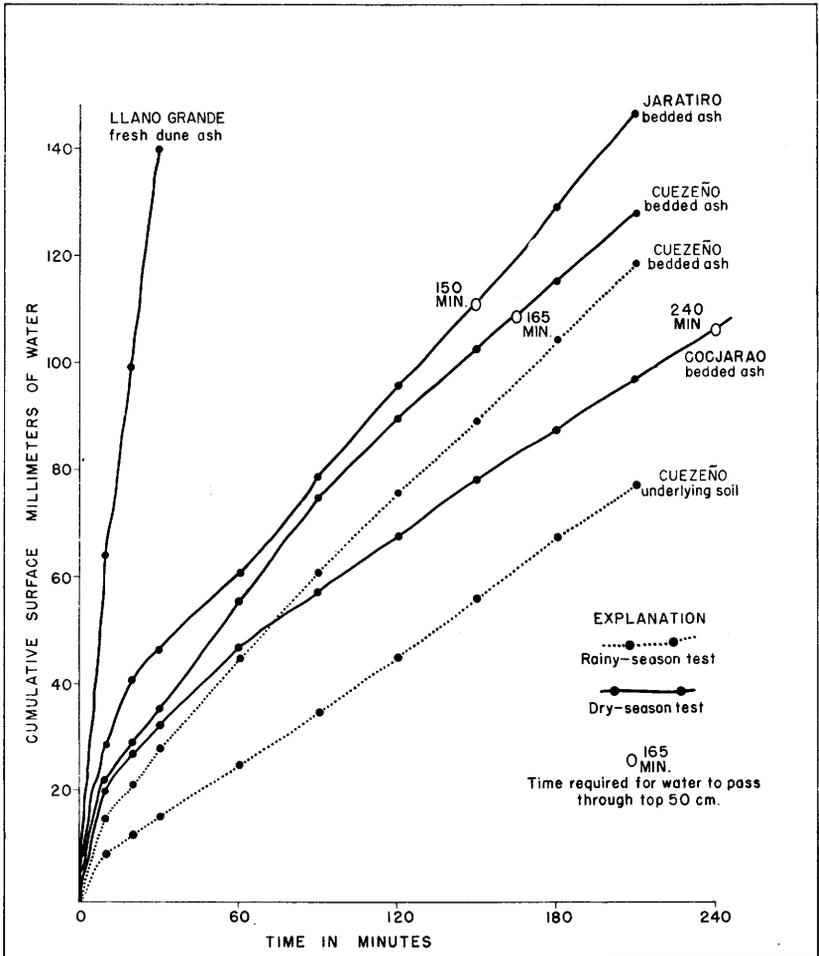
FIGURE 16.—Cumulative infiltration curves for undisturbed ash from Parícutin and preexisting soil.

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 un-crusted, 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 tur-bidity 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 un-crusted 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 at-mosphere 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 rain-drops must have freed and floated to the surface small quantities of the finest particles.

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).
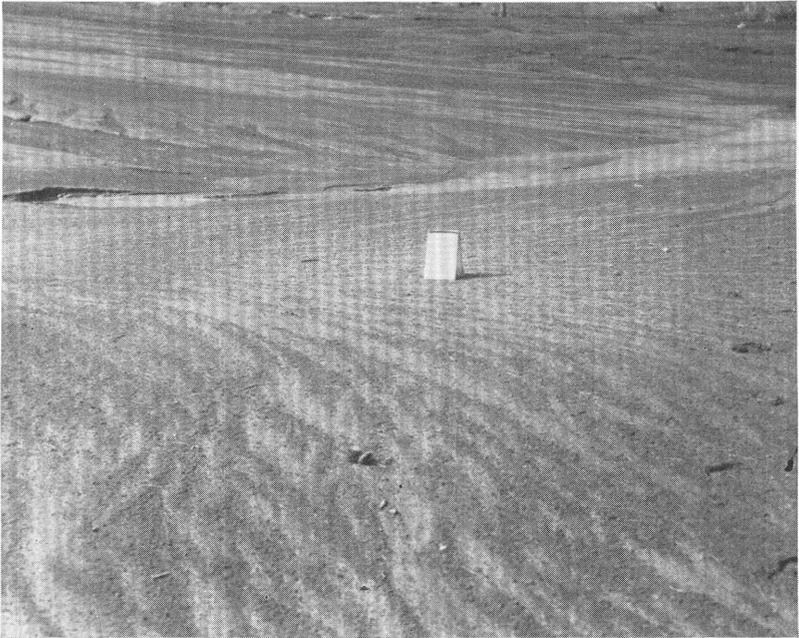
FIGURE 17.—Flow marks on a small alluvial fan at base of Cerro de Capatzun, near Paricutin.
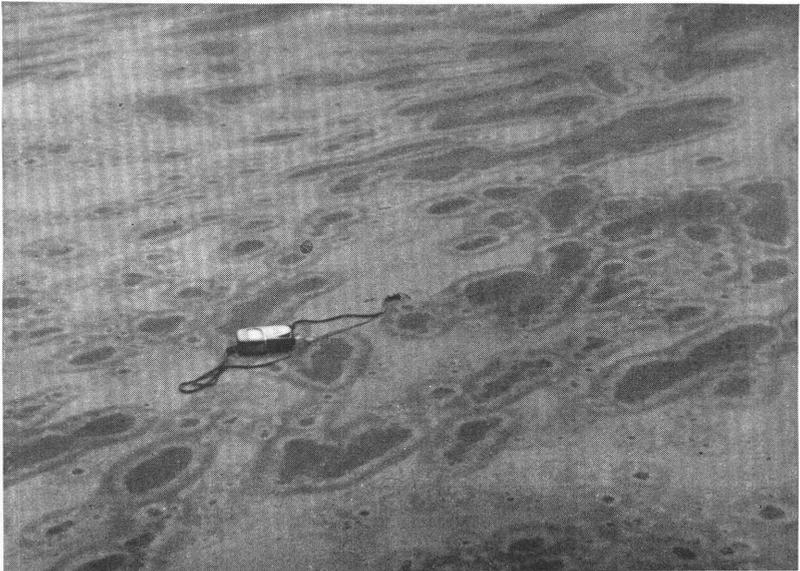
FIGURE 18.—Blotchy pattern, due to differential drying, on surface of mantle of ash from Paricutin.

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 Paricutin.
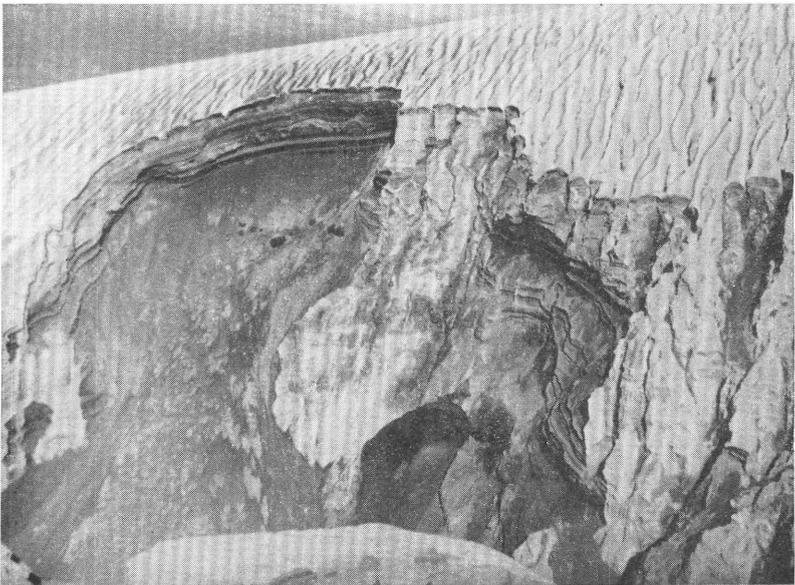

FIGURE 20.—Head wall of a landslide in deep ash from Paricutin.

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.
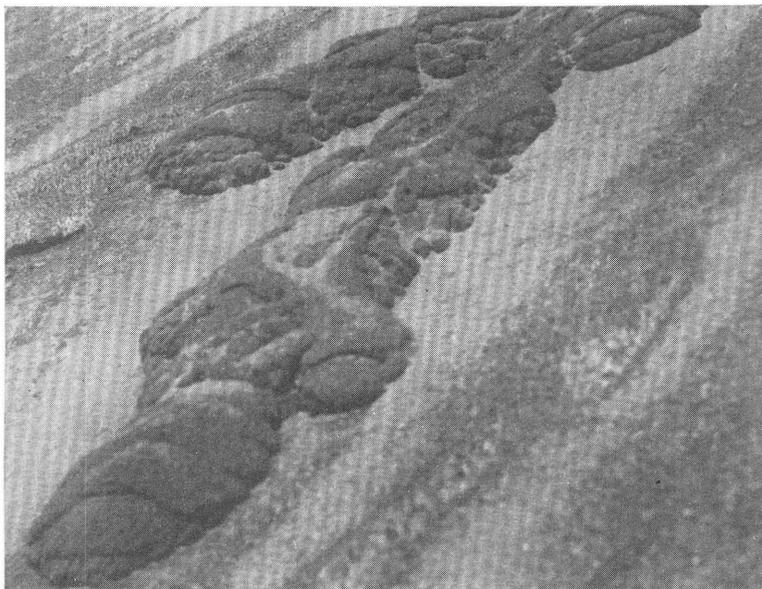
FIGURE 21.—Mudflows between Jarátiro and Parícutin.

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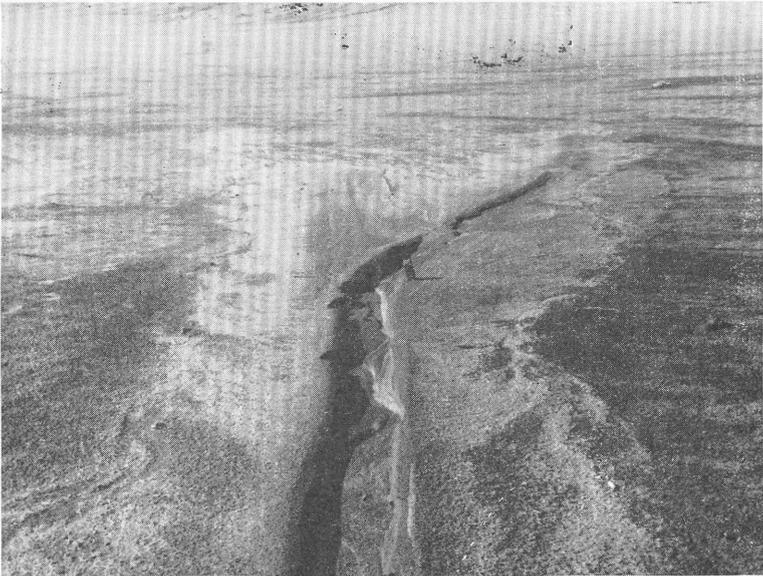
FIGURE 23.—Channel erosion of a mudflow furrow in the Parícutin area.

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.
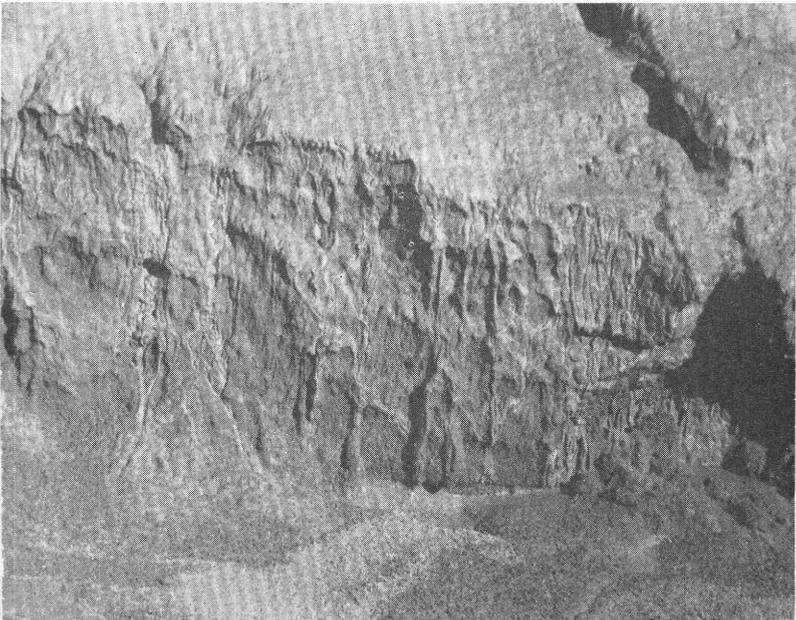
FIGURE 25.—Drips of clay-size ash formed on the vertical bank of an arroyo in the Parícutin area.
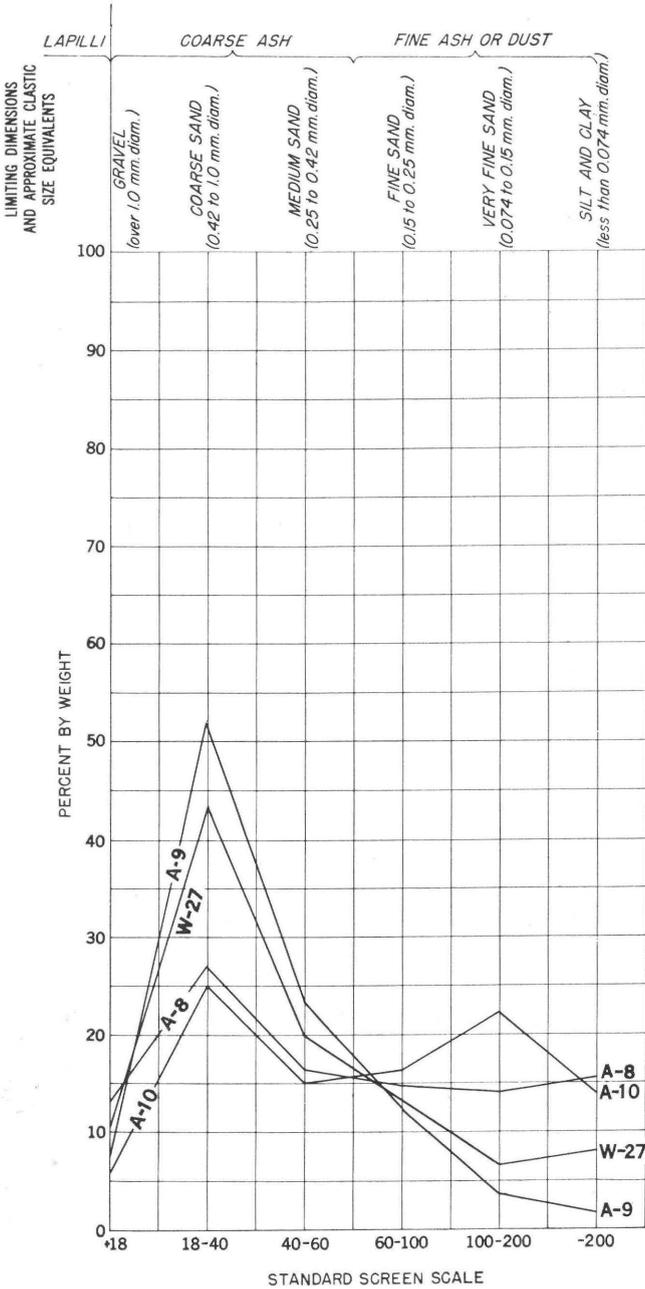
FIGURE 26.—Graph showing size distribution of particles in four mudflow samples from the Parícutin area.

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 Paricutin, 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 s ope 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).
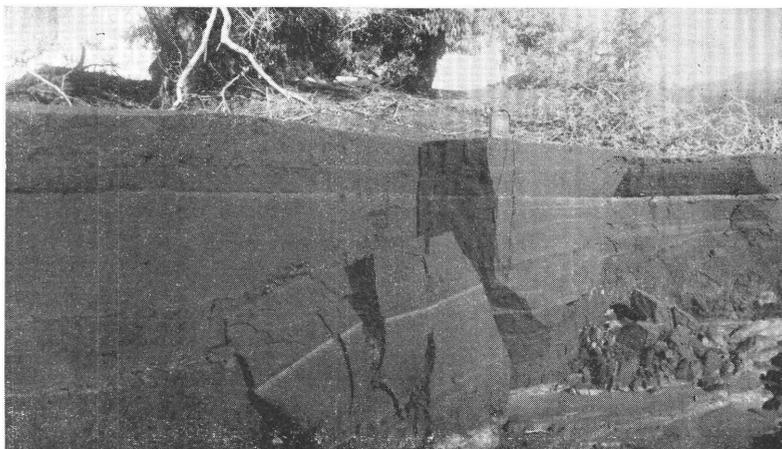

FIGURE 29.—Angular blocks left by stepwise caving along the bank of Arroyo de Corucjuata, in the Parícutin area.

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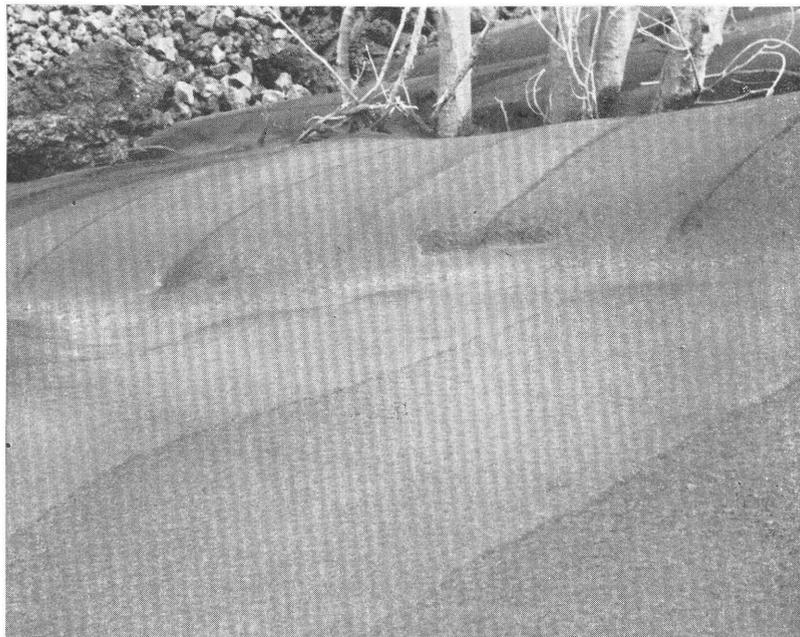
FIGURE 31.—Tension cracks in the mantle of ash from Parícutin produced by the weight of the adjacent lava flow.

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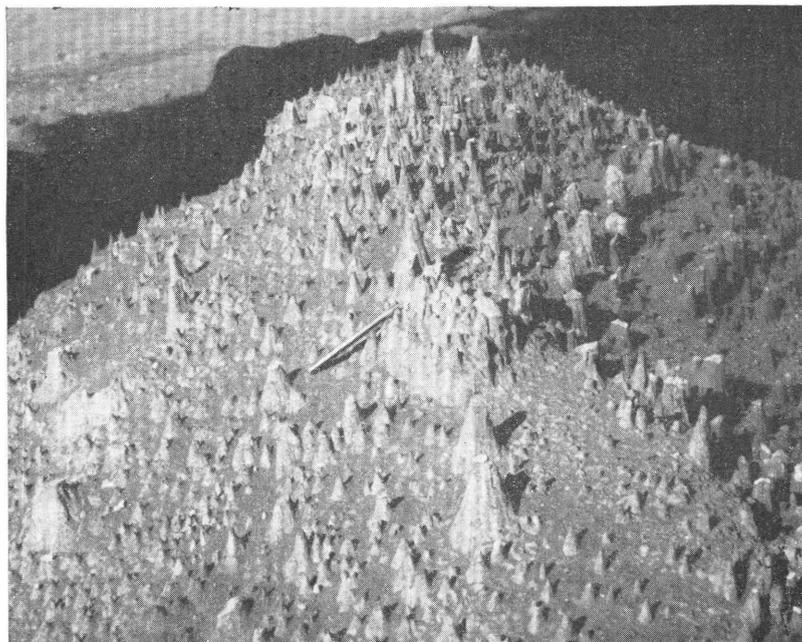
FIGURE 32.—Small bits of broken rock thrown on top of ash from Parícutin at the side of a road have prevented splashing raindrops from eroding the ash underneath them.

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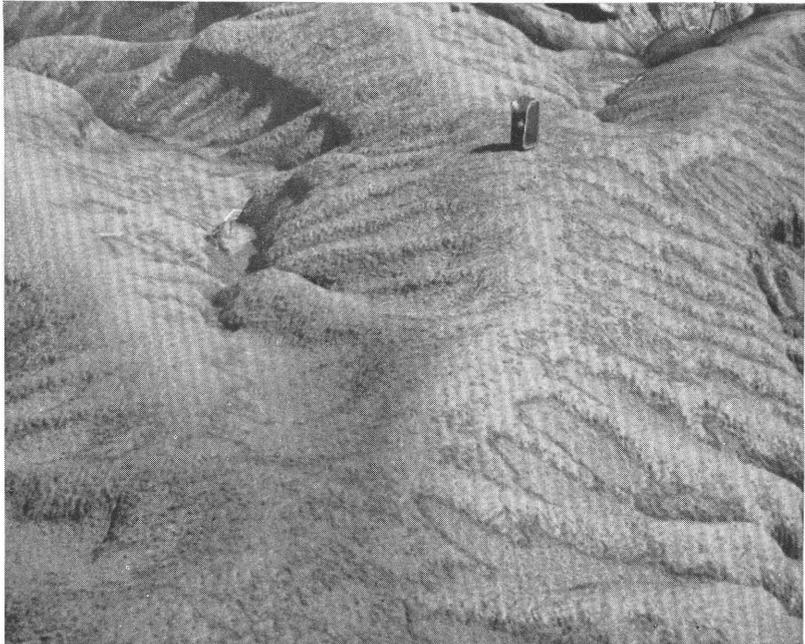
FIGURE 33.—Converging rill heads at crest of a ridge about 2 kilometers south of Parícutin, where the ash is very thick.

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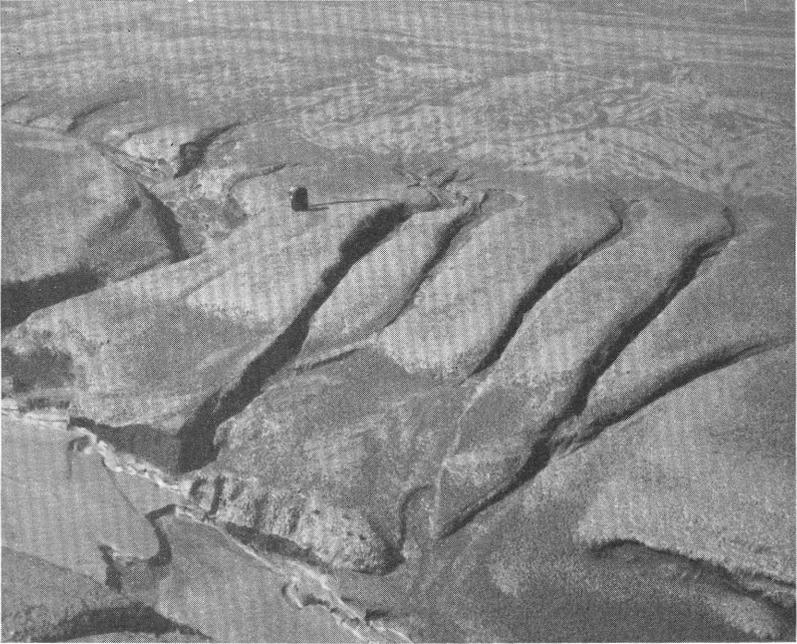
FIGURE 35.—In vicinity of Parícutin. Flat area at top of picture is sheet-eroded, whereas lower, steeper part of same slope is an area of rill erosion.

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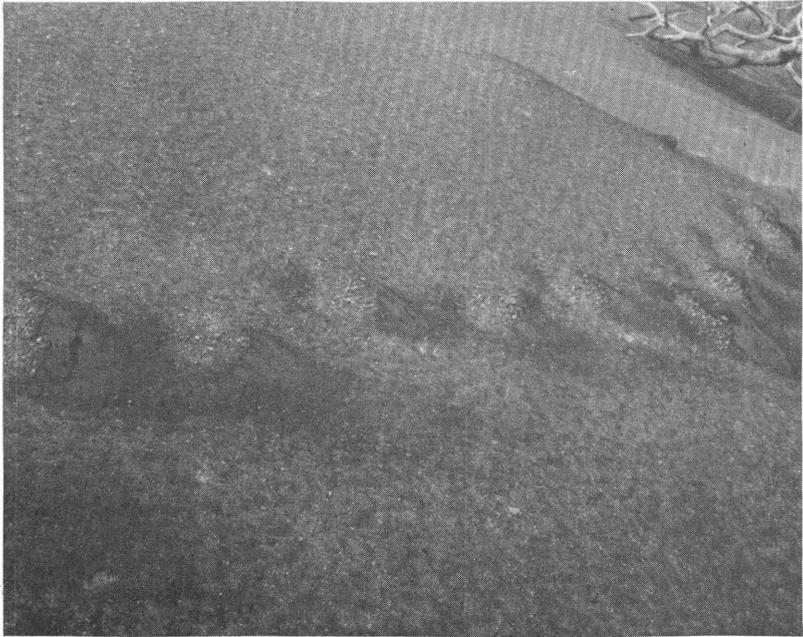
FIGURE 37.—Week-old footprints in ash from Parícutin, showing how artificially steepened slopes cause crusting of the ash on the downhill side of the print.

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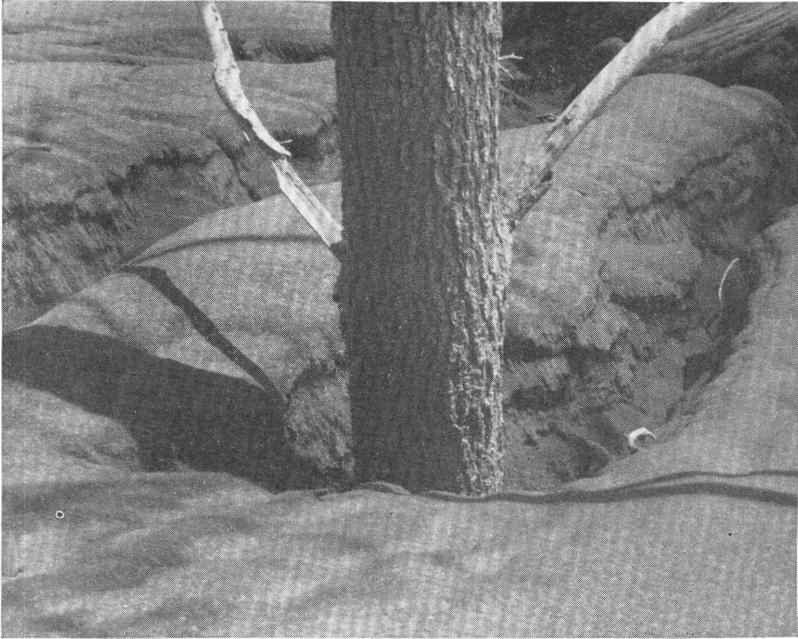
FIGURE 39.—Rill erosion initiated in the Paricutin area by rain water running down a tree trunk.

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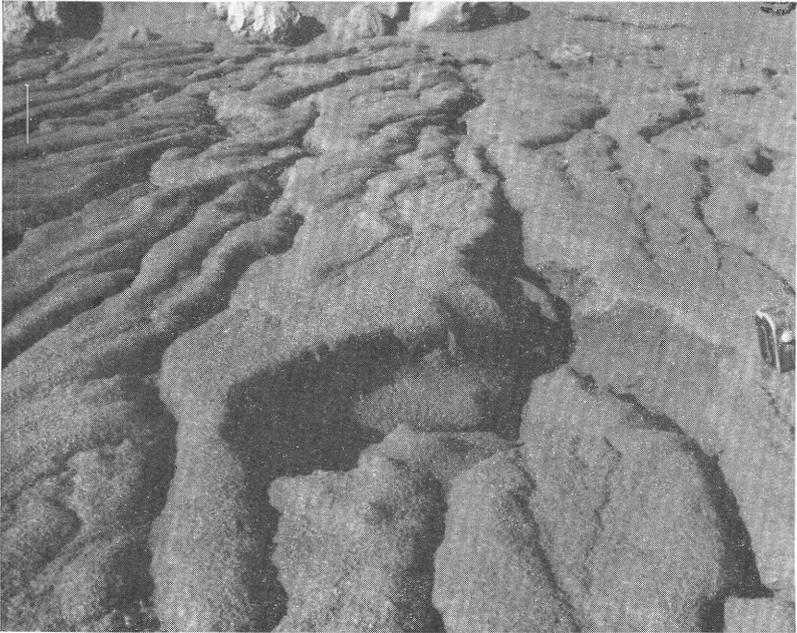
Figure 40.—View looking down slope at rill channels in an area near Parícutin pitted with bomb-impact craters.

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.

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 Capánguito, 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
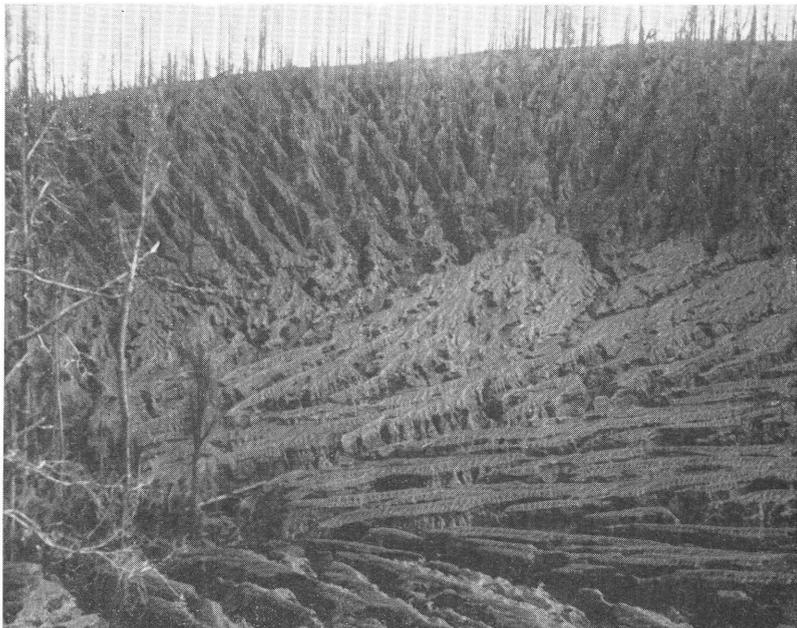

FIGURE 41.—Breached crater of a youthful cone southwest of Parícutin, where ash is 2.5 meters thick showing oak-leaf faceting of interfluves on far slope.

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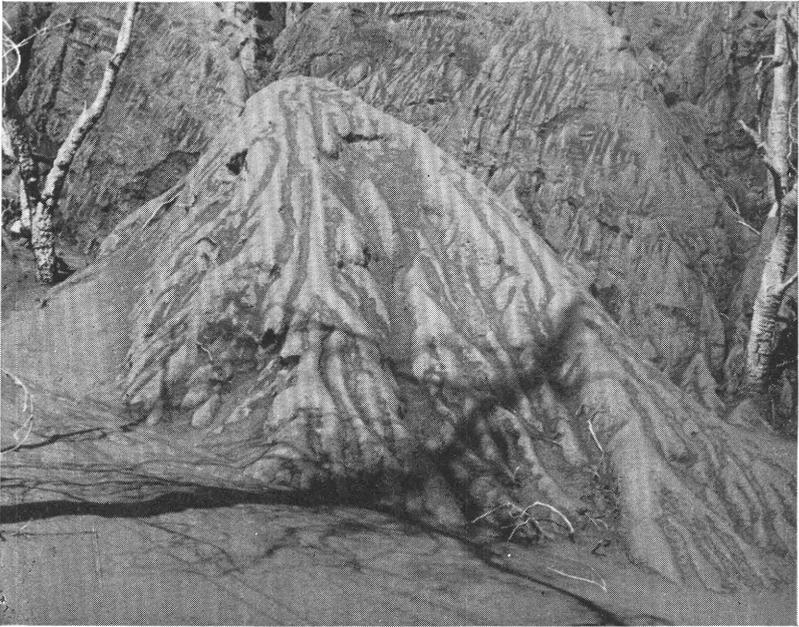
FIGURE 42.—Lower end of interfluve in Parícutin area nearly isolated from upper part by erosion.

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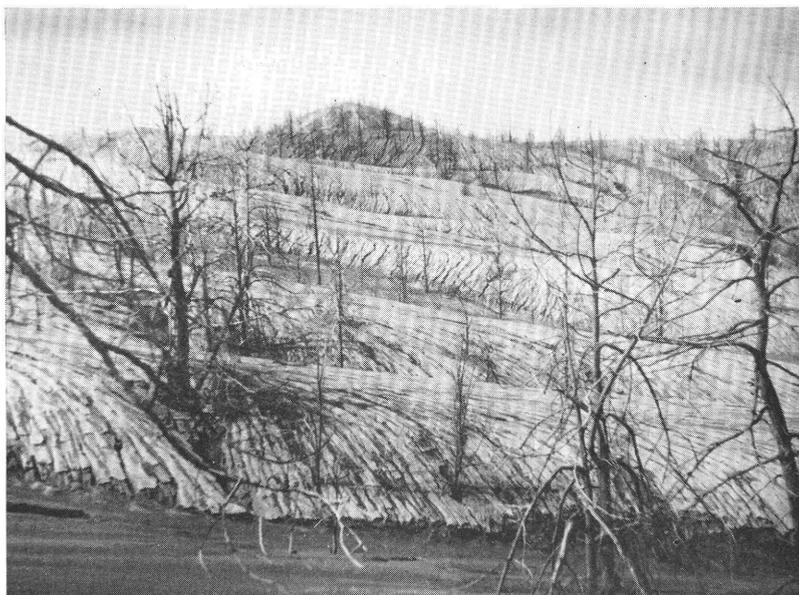
FIGURE 43.—Series of parallel ridges in Parícutin area from which stream channels curve off to either side in response to slope direction.

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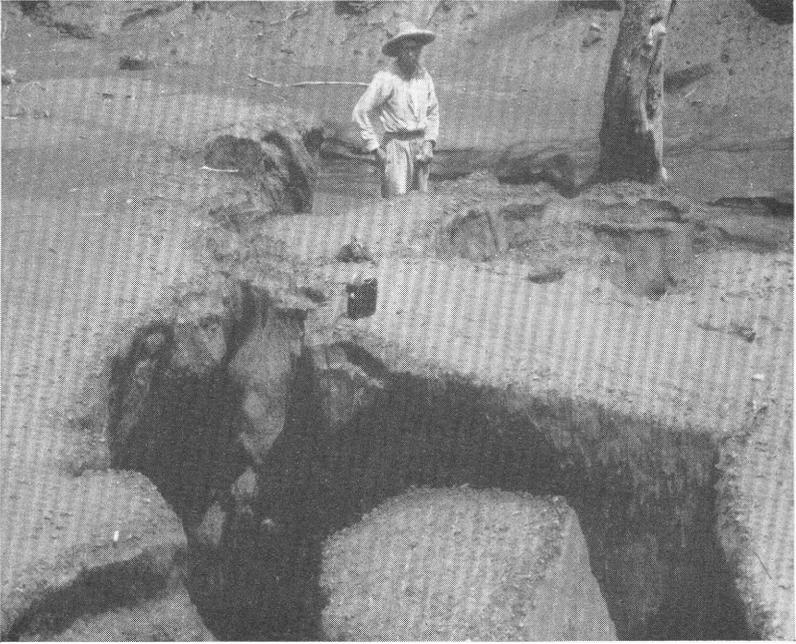
FIGURE 46.—Covered channel in Parícutin area formed by rapid erosion of coarse underlying beds.

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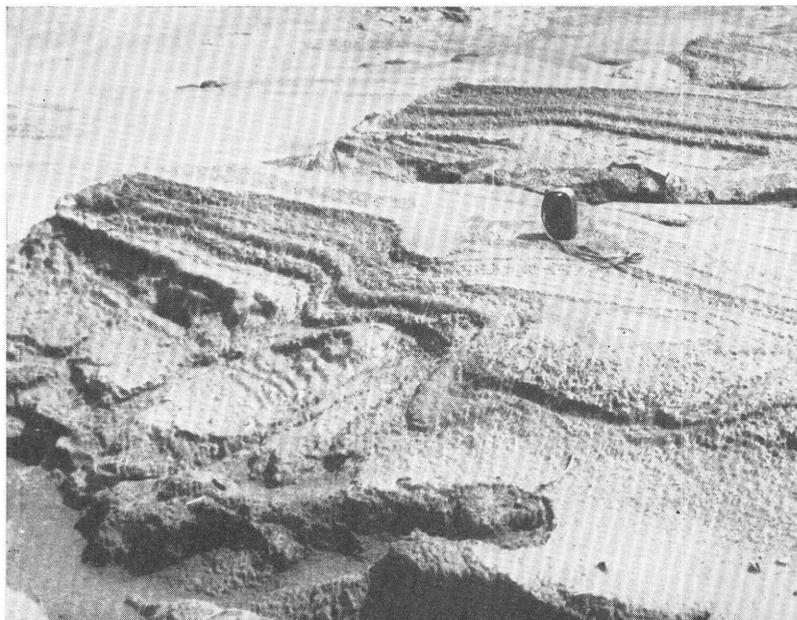
FIGURE 47.—Exposure of beds of ash from Parícutin along the bank of a stream.

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 Capánguito, 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 Paricutin*

Place of observation	Gradient of stream bed (percent)	Low stage					High stage				
		Width (meters)	Depth (meters)	Velocity (meters per second)	Volume (cubic meters per second)	Percent of height of solids column to height of sample	Width (meters)	Depth (meters)	Velocity (meters per second)	Volume (cubic meters per second)	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 / 2.3	1.6 / 5.5	.06 / .50	.95 / 2.0	.10 / [2] 5.5	} 1.0	8.0	.75	3.1	12.4	78.8 (W–11) [3]
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.
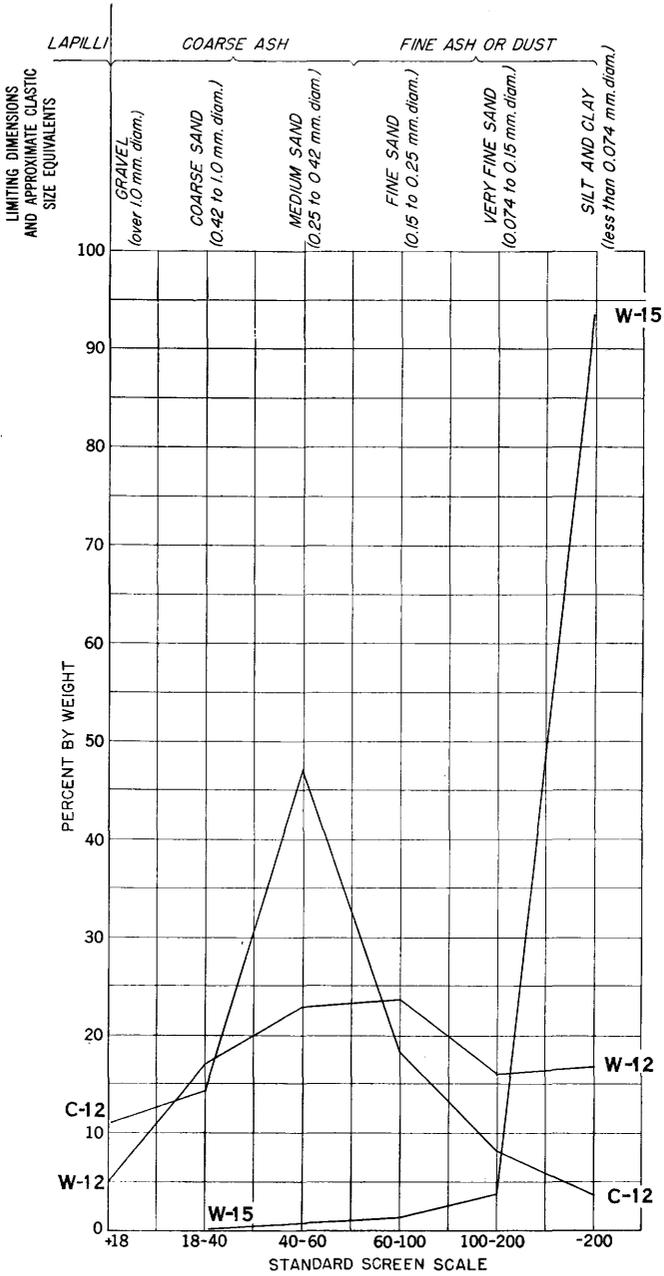
FIGURE 48.—Graph showing size distribution of particles in solid fraction of two stream-flow samples and one water-deposited sample from the Río de Itzícuaro, west of Paricutin.

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
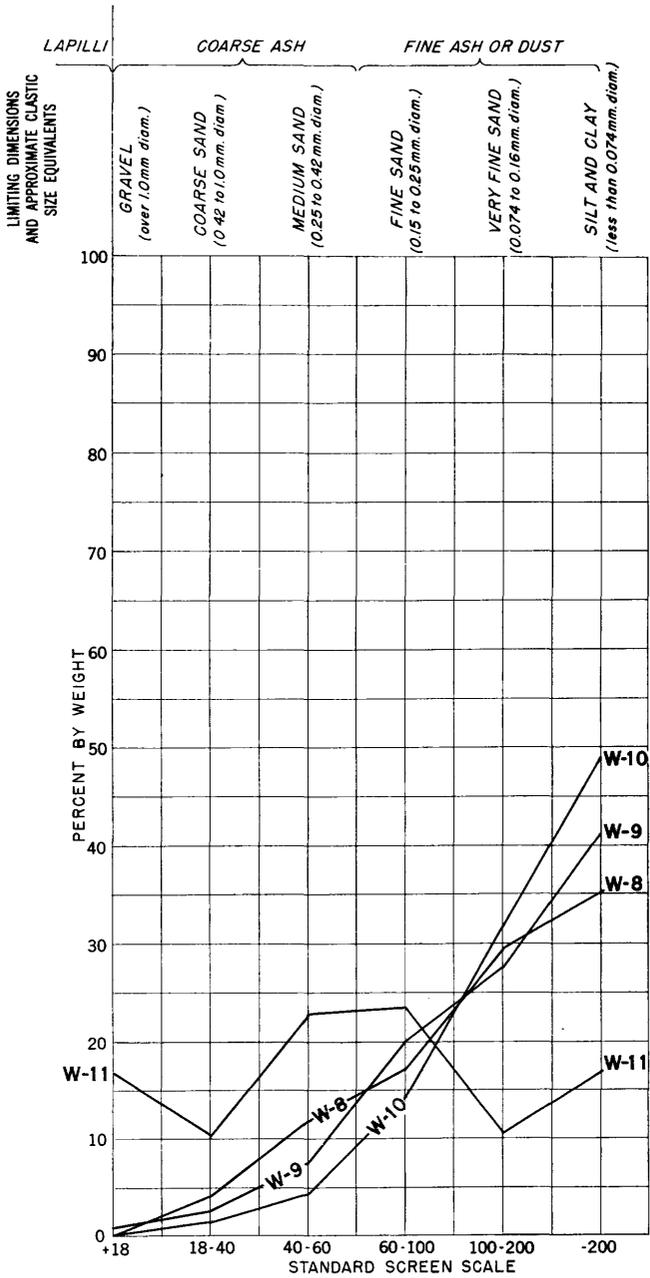
FIGURE 49.—Graph showing size distribution of particles in solid fraction of four stream-flow sample collected near Zirosto, in the vicinity of Parícutin.
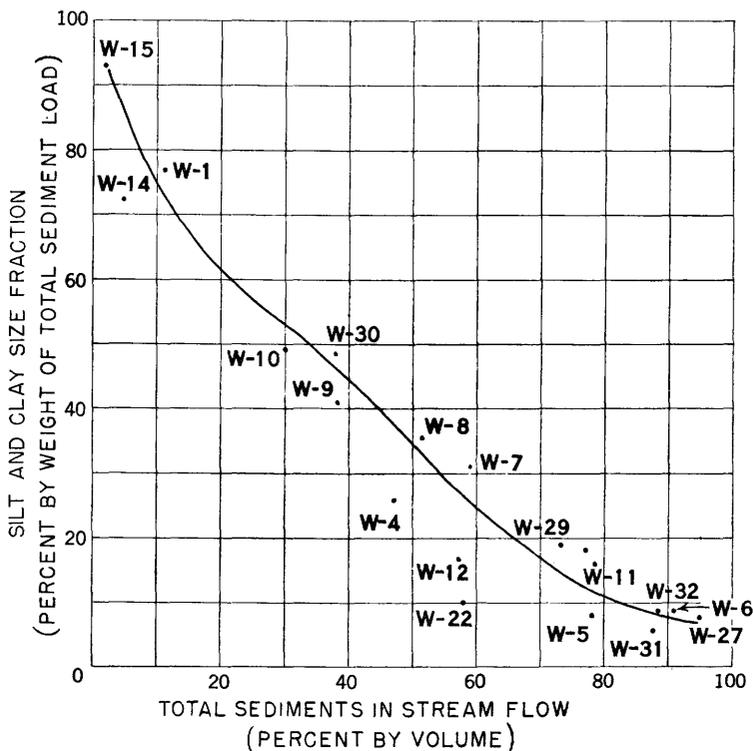
FIGURE 50.—Graph showing relation between total sediment load and percentage of silt-and-clay size in solid fraction of stream-flow samples taken in Parícutin area.

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
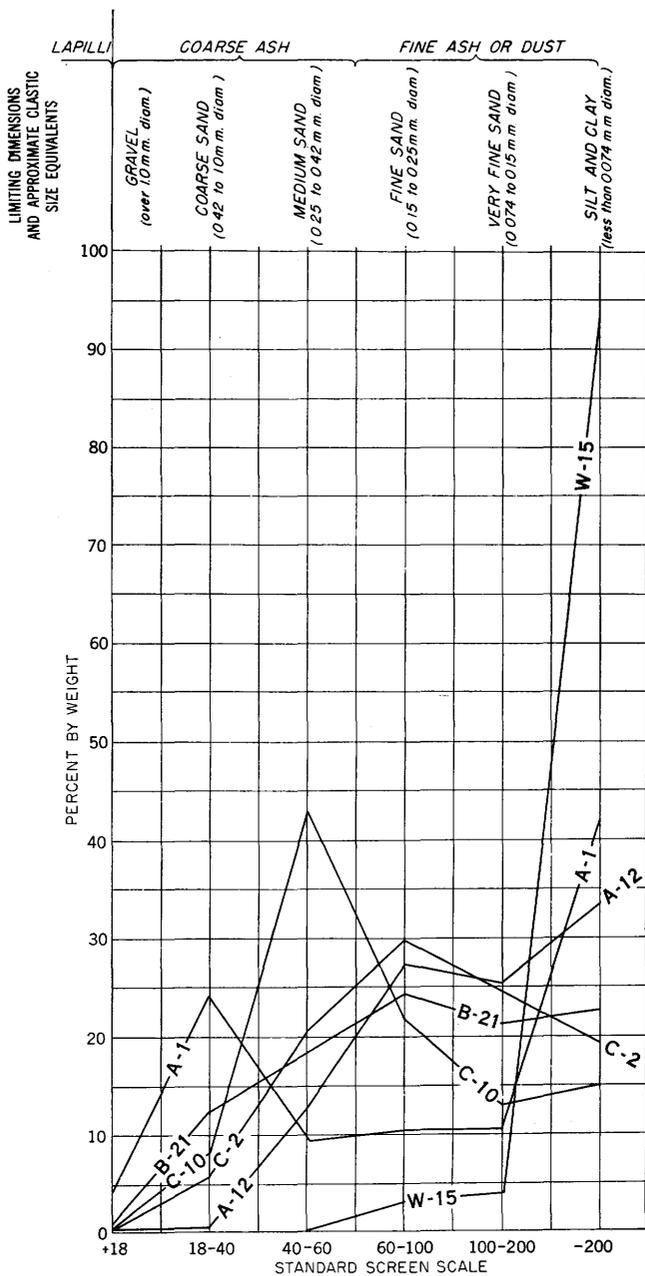
FIGURE 51.—Graph showing size distribution of particles in samples of the finest-grained ash beds and stream-flow solids taken in the Parícutin area.
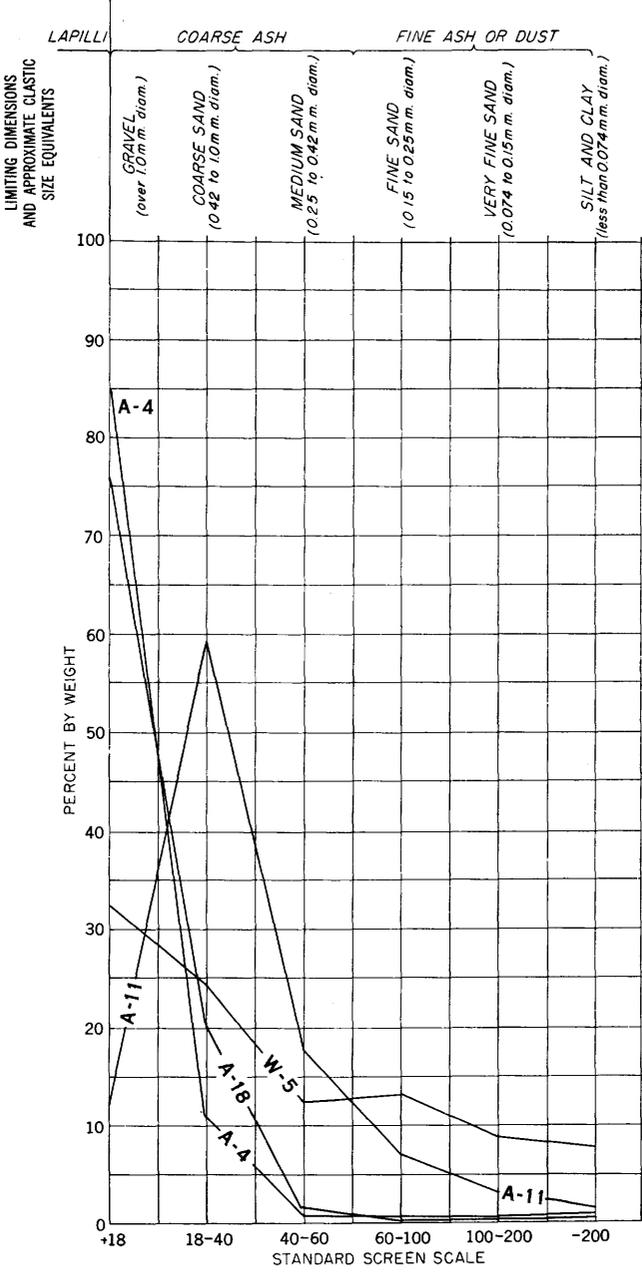
FIGURE 52.—Graph showing size distribution of particles in samples of the coarsest-grained ash beds and stream-flow solids taken in the Paricutin area.

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

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 water-shed 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 Peri-bán, 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 Paricutin 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
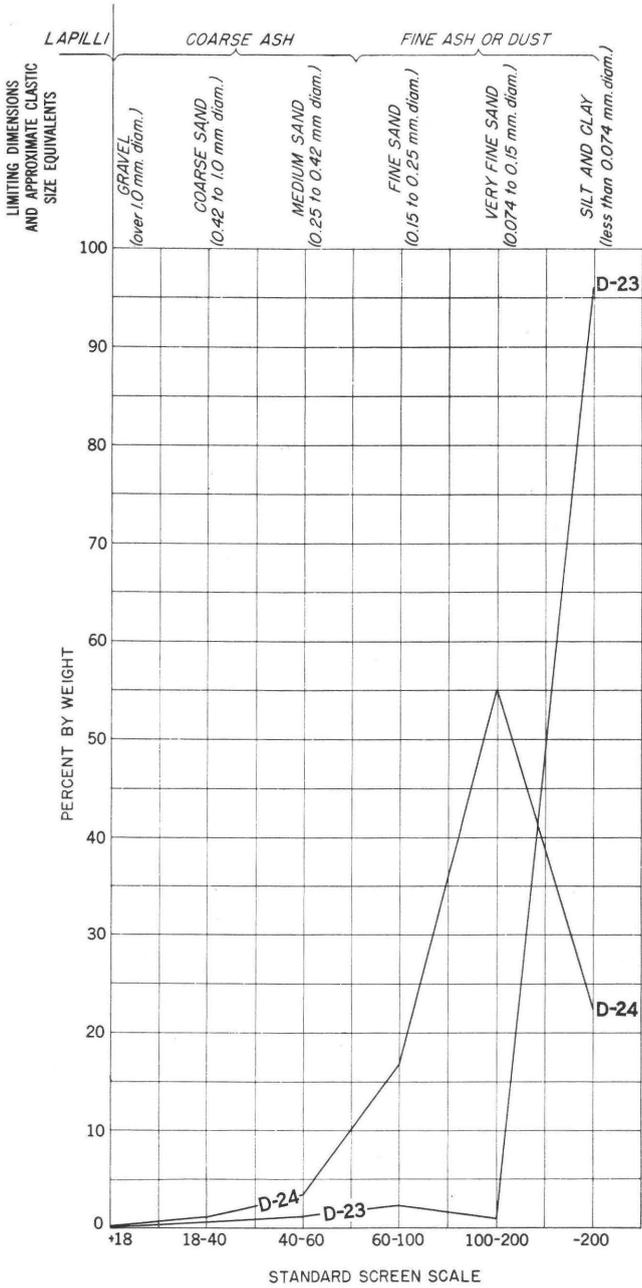
FIGURE 57.—Graph showing size distribution of mud-crack material and noncracking lacustrine material in Parícutin area.

FIGURE 58.—Pattern of mud cracks of the type most commonly seen on lacustrine deposits of ash from Paricutin 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 Paricutin 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.
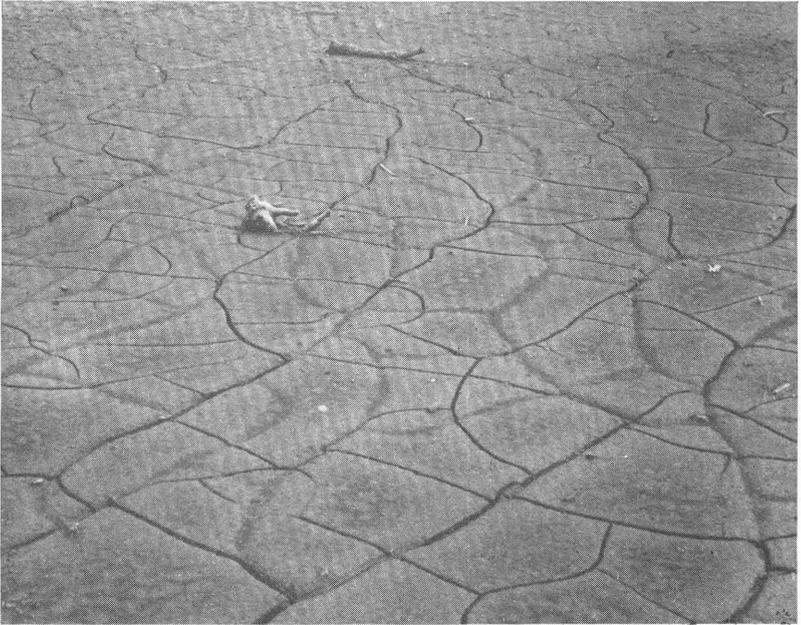
FIGURE 59.—Two sets of mud cracks at Chórotiro, near Parícutin, showing how the well-defined newer cracks fail to follow the pattern of the older, filled cracks.

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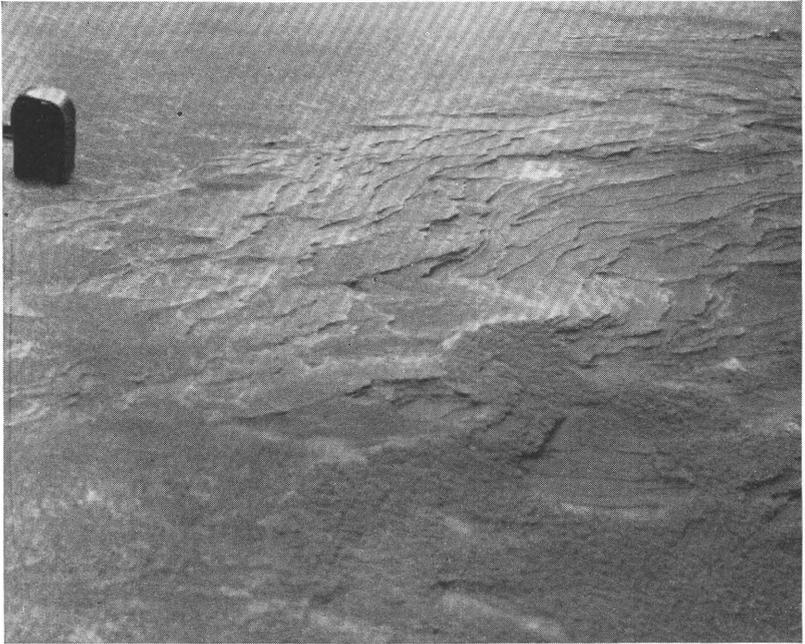
FIGURE 60.—Beds of ash from Parícutin, exposed and partly removed by wind deflation.

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 prin-

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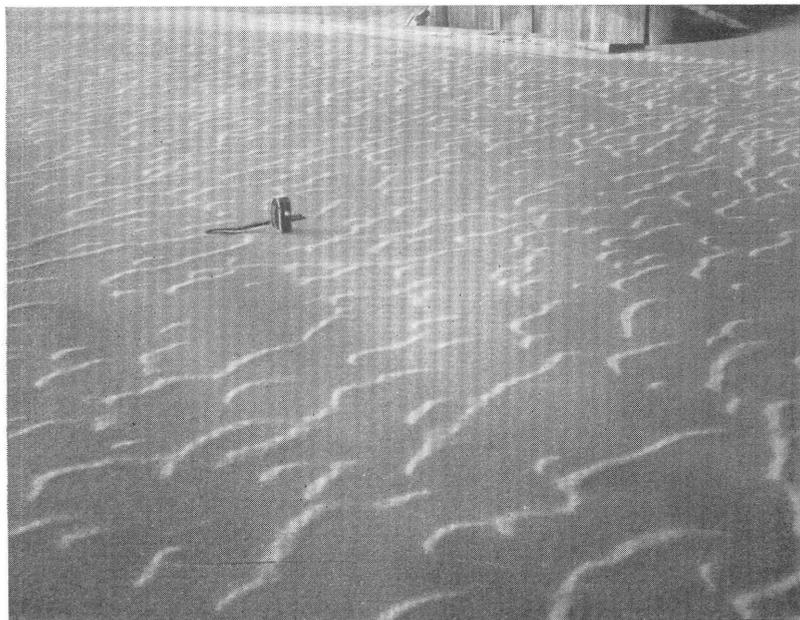
FIGURE 61.—Barchans in miniature at Sinámicbu, near Parícutin. The wind forming them blew from left to right.

elongated across the course of the wind with their irregular lobes pointing leeward (fig. 62). The larger dunes are also of the barchan
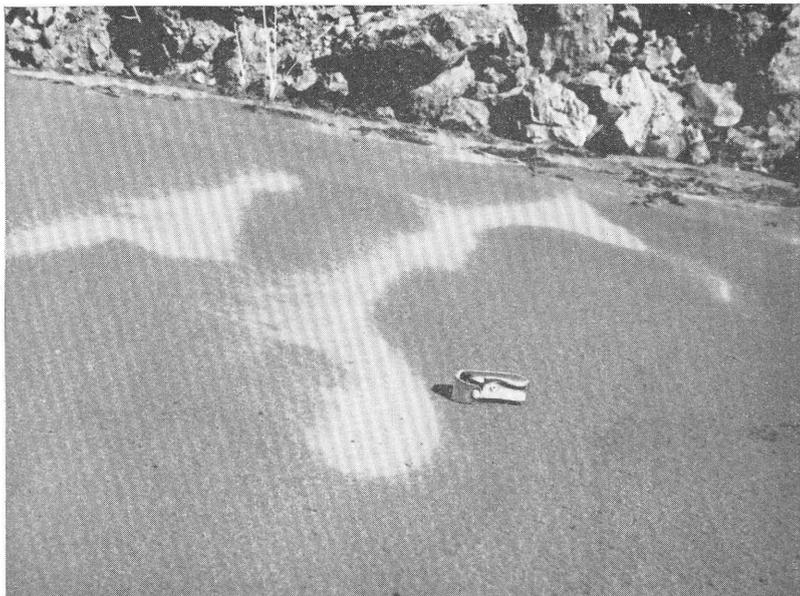
FIGURE 62.—Small dunes in the Paricutin area, elongated across the course of the wind with lobes pointing leeward.

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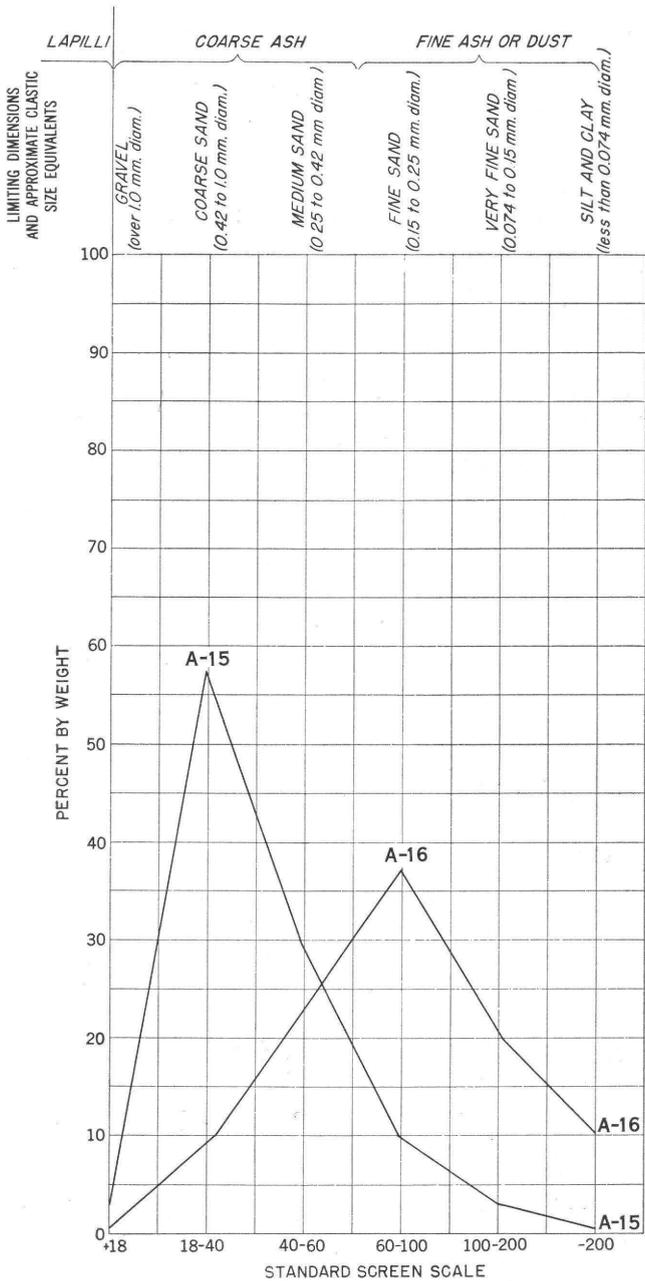
FIGURE 63.—Graph showing size distribution of particles in samples of wind ripples near Parícutin and of the surface between them.

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,
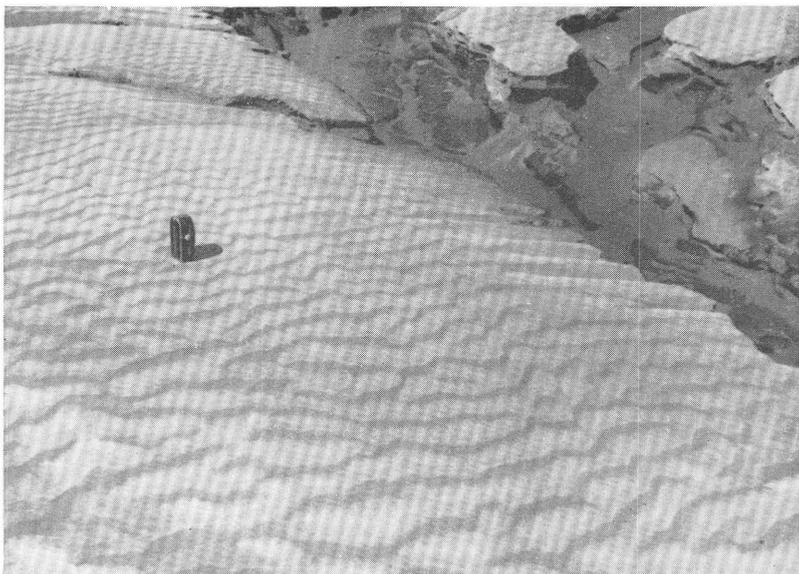
FIGURE 64.—Ripples formed on an arroyo bank in the Parícutin area by winds from different directions.
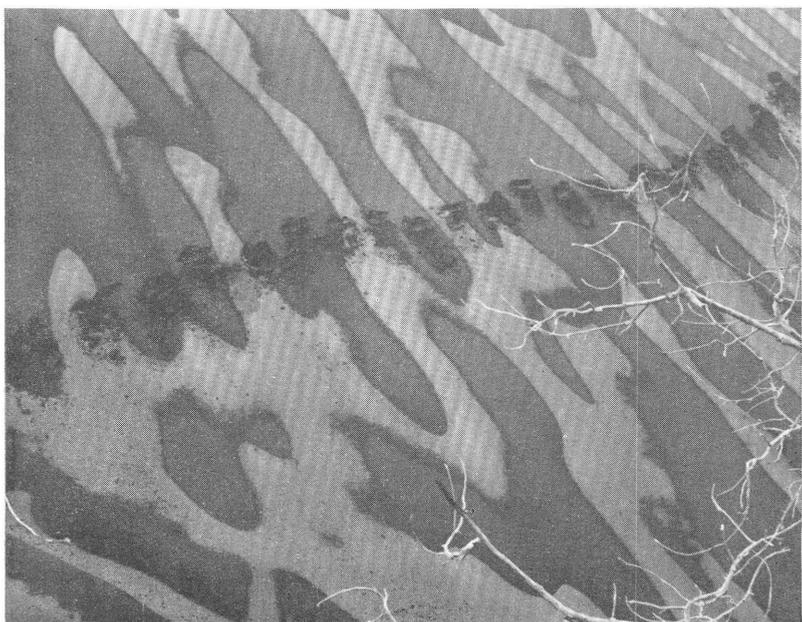
FIGURE 65.—Accumulations of dry ash from a new Parícutin eruption on an uneven surface of damp ash.

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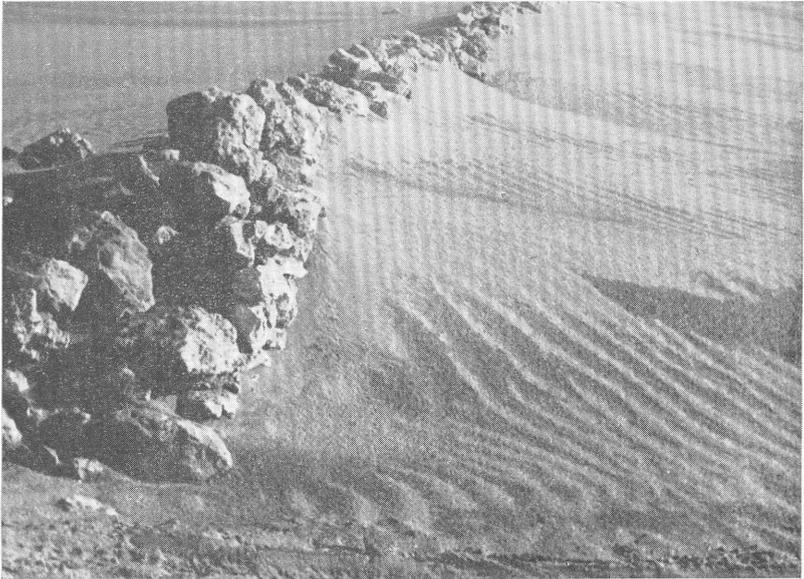
FIGURE 66.—Stone fence on Llano Grande nearly buried by wind-drifted ash from Paricutin.

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 inter-bedded 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 com-pletely 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 ac-

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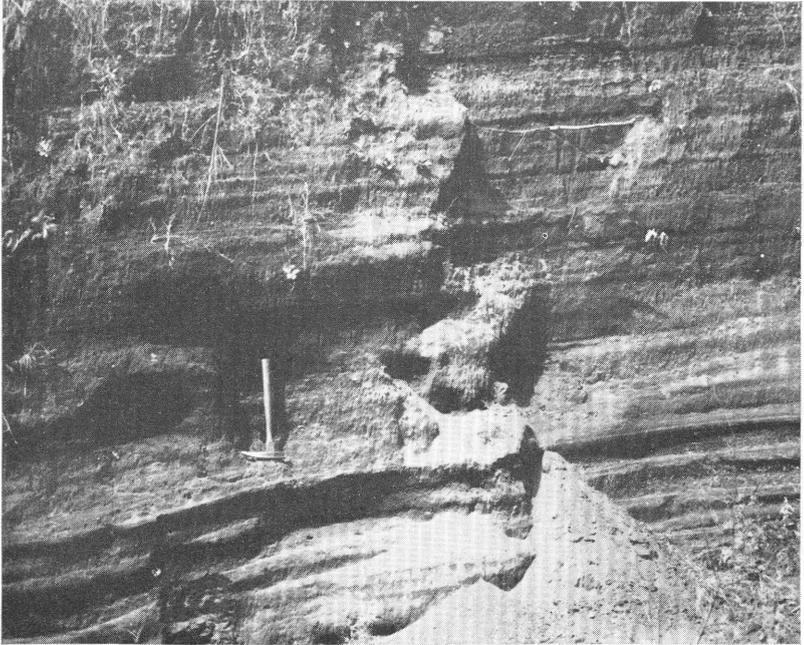
FIGURE 68.—Bedding in ash from Jorullo exposed in Barranca Puerca, south of the cone.

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).
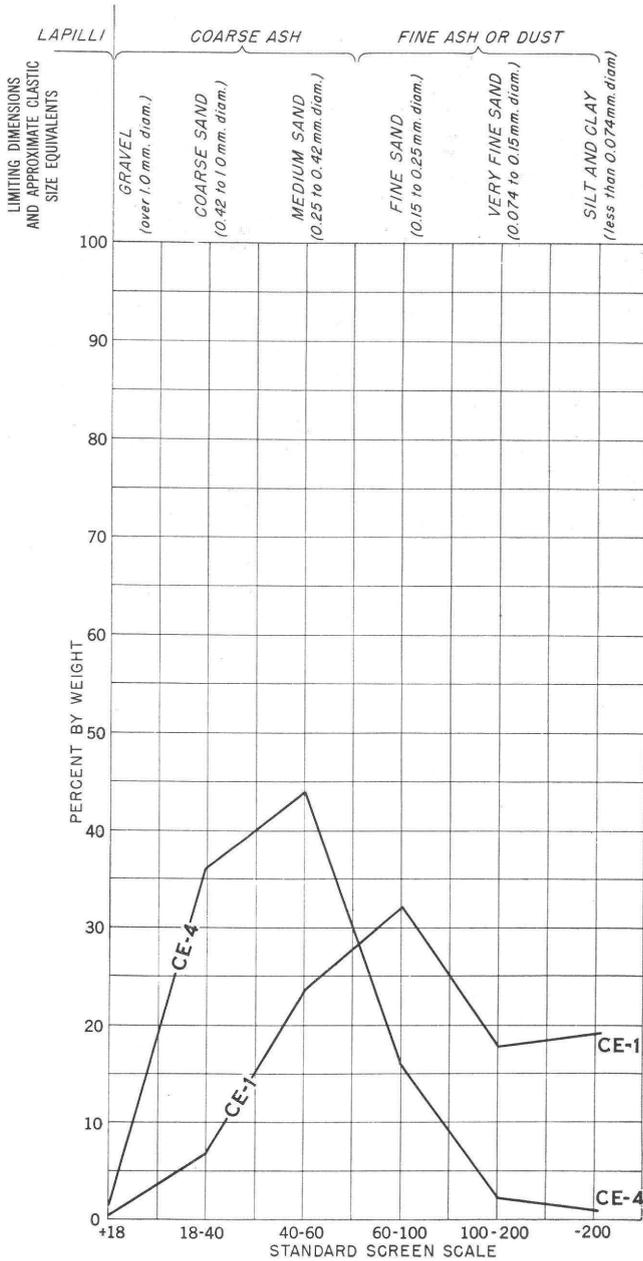
FIGURE 70.—Graph showing size distribution of particles in samples taken from surface at south base of Ceboruco (CE–1) and from surface between inner and outer craters (CE–4).
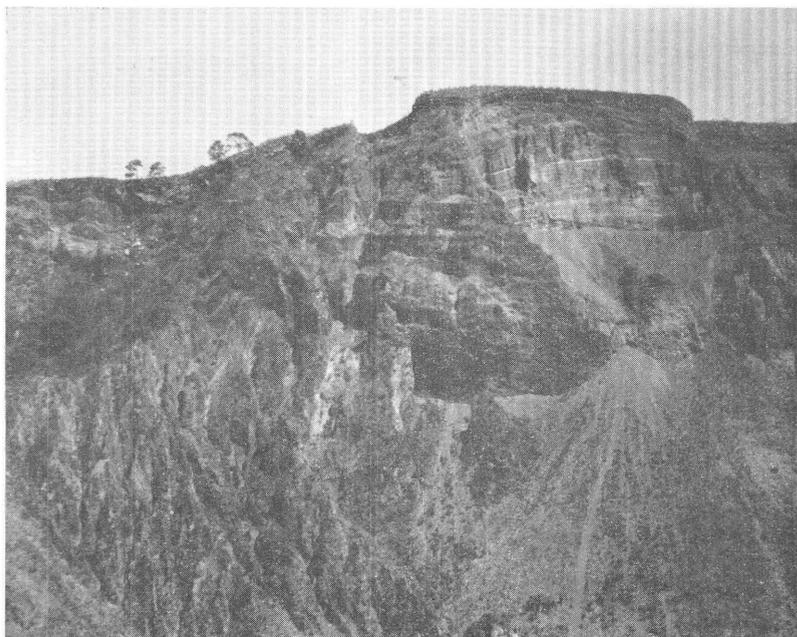
FIGURE 71.—Bedding of ash exposed by a landslide on the west face of La Coronilla, highest inner crater of Ceboruco.

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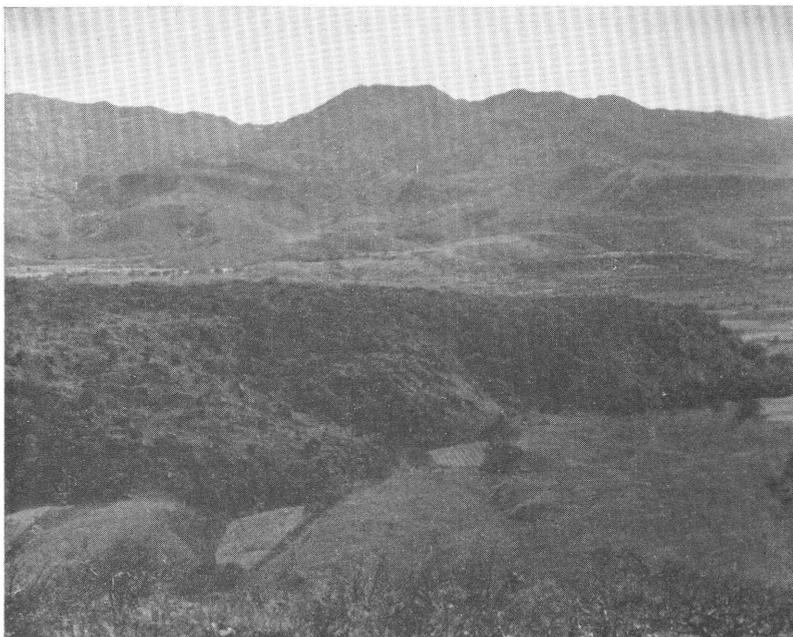
FIGURE 73.—Barrancas dammed by a lava flow from Ceboruco and filled with alluvium have become cultivated fields.

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 pre-existing 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 játsakuɹini* (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

153

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.
Curingüaro.   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. cf 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

TEMPERATURE
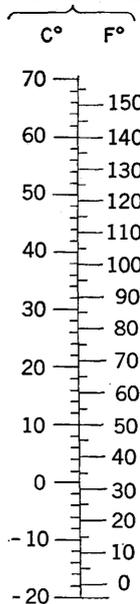
LINEAR MEASURE
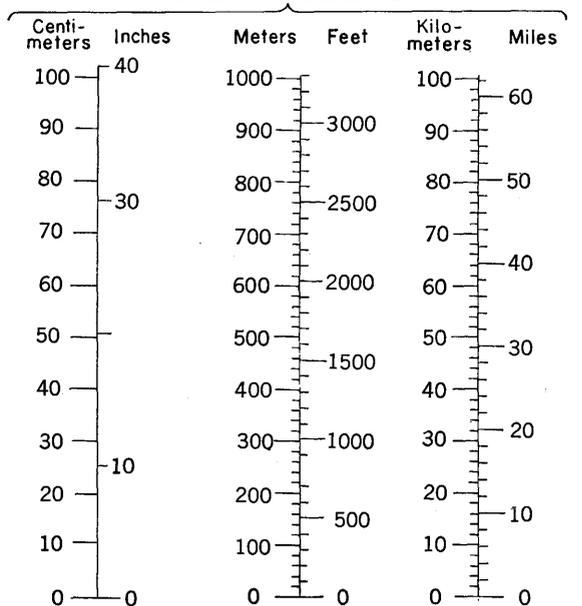
WEIGHTS

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

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

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

1 km. = 0.6214 mile
1 mile = 1.6093 km.
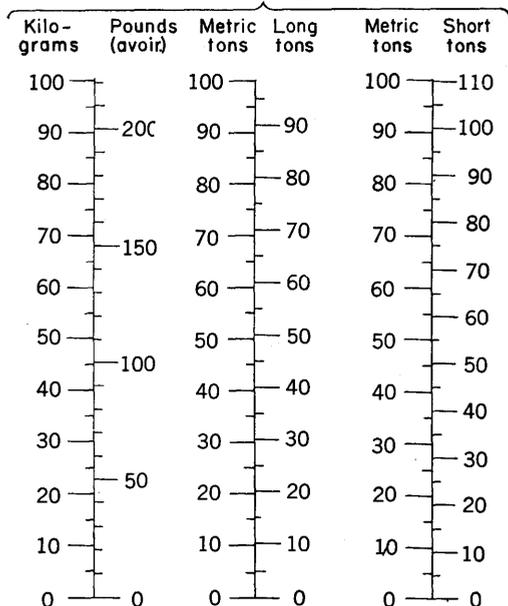
1 kg. = 2.2046 lb.
1 lb. = 0.4536 kg.

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