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The geomorphological evolution of the Paricutin cone and lava flows, Mexico, 1943–1990

Moshe Inbar[a], Jose Lugo Hubp[b], Lourdes Villers Ruiz[b]

[a]*Department of Geography, University of Haifa, Haifa, Israel*

[b]*Institute of Geography, Universidad Nacional Autonoma de Mexico, Mexico City, Mexico*

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Abstract

Erosion and sedimentation processes in the Paricutin cone and adjacent lava fields have been evaluated 47 years after the eruption through field study of the morphological characteristics of the area. Previous studies indicate an initial stage of accelerated erosion, decreasing quickly after the stripping of the ash layers and cessation of the volcanic activities. In the cone and crater area, revegetation is the main process, after the first stage of stripping of fine ash. The lava fields are the least affected areas by erosional processes, with vegetation development in minor depressions, crevices and along the edges of the lava flows. The "llanos" or lava dammed plains, are the most active physiographic units, with continuous deposition of sediments. They are completely covered by vegetation or under agricultural use. Incision of channels along the lava field edge promotes the integration of the drainage system, but still most of the affected area drains into the lava field. Present erosion rates are higher than normal rates, and a complete rehabilitation of the pyroclastic area may extend over decades. Filling of sediments and revegetation of the lava fields will develop in a longer period of several millennia.

1. Introduction

The evolution of landscape over time is a central aspect of geomorphological studies. Recent volcanic features offer the opportunity to monitor the processes and development of the landscape. The Paricutin eruption occurred in the state of Michoacan, Mexico, between the years 1943 to 1952, and was one of the most studied and documented volcanological phenomena in the past fifty years.

Erosional processes on the landscape created by the eruption were studied by Segerstrom (Segerstrom, 1950, 1960, 1961, 1966) who, during the first 20 years after the eruption, conducted a detailed study on erosion and sedimentation in the area; a short study was reported by Lowdermilk (1947), and a detailed report of the effects of the first year was written by Arias Portillo (1945). Since 1965 until 1987 no further monitoring of erosional processes was reported. A study of longer terms of recovery after eruption was conducted in 1987 and 1990 by the present authors, following previous studies by Segerstrom done up till 1965.

Most of the observations and studies of erosional processes after volcanic eruptions are short-term, following the first period after the eruption. Erosion rates are high, about three to four orders of magnitude above the normal erosion rates for non-affected areas (Swanson et al., 1983; Collins and Dunne, 1986). Several years after eruption, initial rates decrease with stripping of the fine ash layer, vegetation cover and development of a steady drainage system. A rapid decline in the pattern of erosion was found in several recent eruptions, from 25–100 mm/yr in the first two years to 1–5 mm/yr within 5 years of the eruption (Swanson et al.,

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1983). In the Mount St. Helens area, rapid channel adjustment occurred during the first two winters after eruption (Meyer and Martinson, 1989). In lava flows, erosion processes and integration of drainage systems from basaltic lava fields are slow and may take centuries or thousands of years, as no integrated drainage is found in the 1790 eruption of the Kilauea lava flows (Malin et al., 1983) and other historically formed lava fields in different world climates, such as the Ceboruco flow in Mexico, Tenerife in the Canarian islands, the Escorial flow in the southern Andes, etc.

In a very detailed study, Segerstrom (1950) described erosional and depositional processes taking place in the areas affected by the eruption. Erosive processes were accelerated as the terrain was unvegetated and covered with unconsolidated ash, permitting observation of processes which are usually slow. We undertook the task of continuing Segerstrom's observations and monitoring of processes after a 40 years interval, emphasizing the long term effect of the eruption and the recovery rates of the different landscapes. The aims of this study are (1) to examine erosion and sedimentation processes in the Paricutin cone and adjacent lava fields, following Segerstrom's work in the first two decades after the eruption; (2) to identify revegetation processes and soil development; (3) to determine the changes in the drainage system and rates of integration after eruption, and (4) to estimate the recovery rate of the different volcanic landforms 50 years after the eruption.

2. The Paricutin area

The Paricutin volcano belongs to the Quaternary Trans-Mexican Volcanic Belt (TMVB) (Lugo et al., 1985; Hasenaka and Carmichael, 1985; Connor, 1987). The area is one of the youngest and most active volcanic fields in Mexico. The maximum density of cinder cones in the TMVB is 19 over 100 km^2 (Lugo et al., 1985) and the median density for the Michoacan–Guanajato area is 5.5 cones for 100 km^2 (Hasenaka and Carmichael, 1985). The Paricutin lies in the southern part of the TMVB, close to the Balsas depression, eleven km southwest of the cone lies the Tancitaro volcano (3840 m), the highest stratovolcano of Michoacan (Fig. 1).

The eruption took place at a height of about 2400 m, on a small plateau formed by volcanic activity during the late Pleistocene which filled the former relief, levelling depressions and raising the altitude of the area.

The climate is humid subtropical, with heavy rains during the summer. Mean annual rainfall is above 2000 mm in the higher regions and around 1800 mm in the plains. Mean annual temperature is 14–16°C; 40 to 60 frost days are registered every year. Runoff is about 100–200 mm. Volcanic soils, andosol type, derived from fine to medium ash cover the volcanic cones and lava flows in the vicinity of the Paricutin (Correa Perez, 1974). The hilly area, composed of young volcanoes and lava flows, is covered by a dense forest; plains are cultivated, mainly with corn and avocado orchards. The town of Angahuan, 6 km northeast of the cone, has a population of around 3800 people.

3. The Paricutin eruption

The eruption started on February 20, 1943, on a flat corn field, 2380 m high, near the village of San Juan Parangaricutiro. An early airphoto dating back to 1934 shows the area morphology and villages before the eruption (Fig. 2). Since February 7 several microseisms were registered by the Tacubaya seismological station in Mexico City, indicating the coming activity. The eruption was thoroughly described by several authors, who followed all the stages since the beginning in 1943 until the end in 1953 (Flores, 1945; Trask, 1945; Bullard, 1947; Segerstrom, 1950; Fries, 1953).

Eruption started from a hollow from which vapors efumed occasionally; on February 20 the eruption started with explosion of pyroclastic materials. On the second day the cone reached a height of 50 m, and a lava flow erupted from the northern part of the cone (Ordonez, 1943). On February 27, the cone was 140 m high, and the lava flows at the beginning of March covered a total area of 0.65 km^2. After the first year, the cone reached an height of 336 m above the original ground. Vegetation was completely destroyed within the 1 m ash isopach which covered an area with a radius of about 9 km length in 1946. Ash covered wide areas, and the 1 mm isopach reached Guadalajara, 180 km northwest of the area (Segerstrom, 1950). Lava flows continued to spread during the years 1944 and 1947. In

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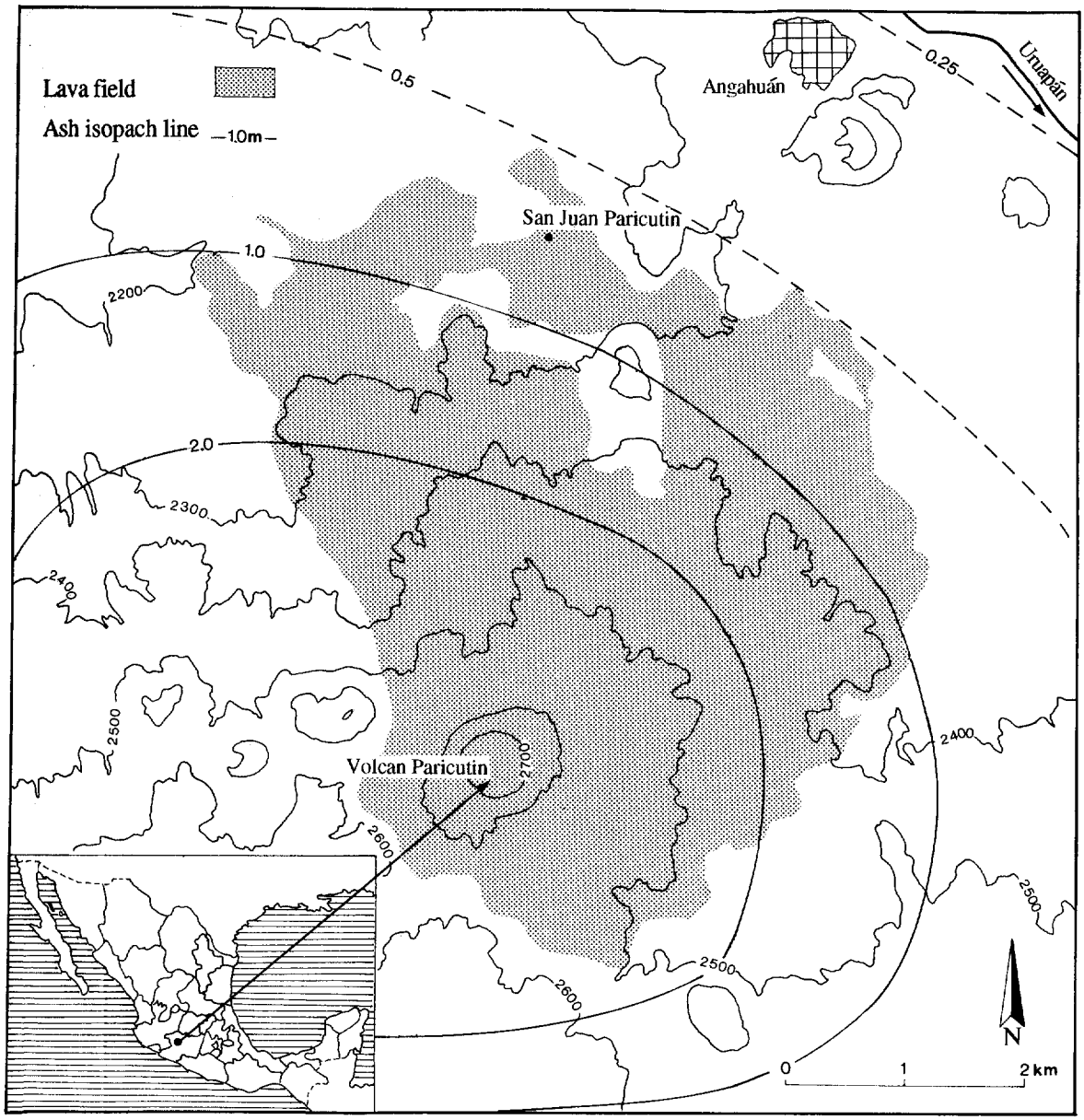


Fig. 1. Paricutin area and location map. Lava field surrounding the volcano covers 25 km^2. Isopach lines show ash depth in 1946.

October 1944 the Sapichu parasitic cone erupted until it was covered by lava flows and the main Paricutin cone renewed its activity. The last activity occurred in March 1952, after 9 years and two weeks of activity, but the main morphological development occurred in the first four months.

4. The Paricutin cone and crater

The present morphometric parameters of the Paricutin cone were obtained from 1:50,000 topographic maps, airphotos and field measurements. The cone height is 280 m above the ground on the western side;

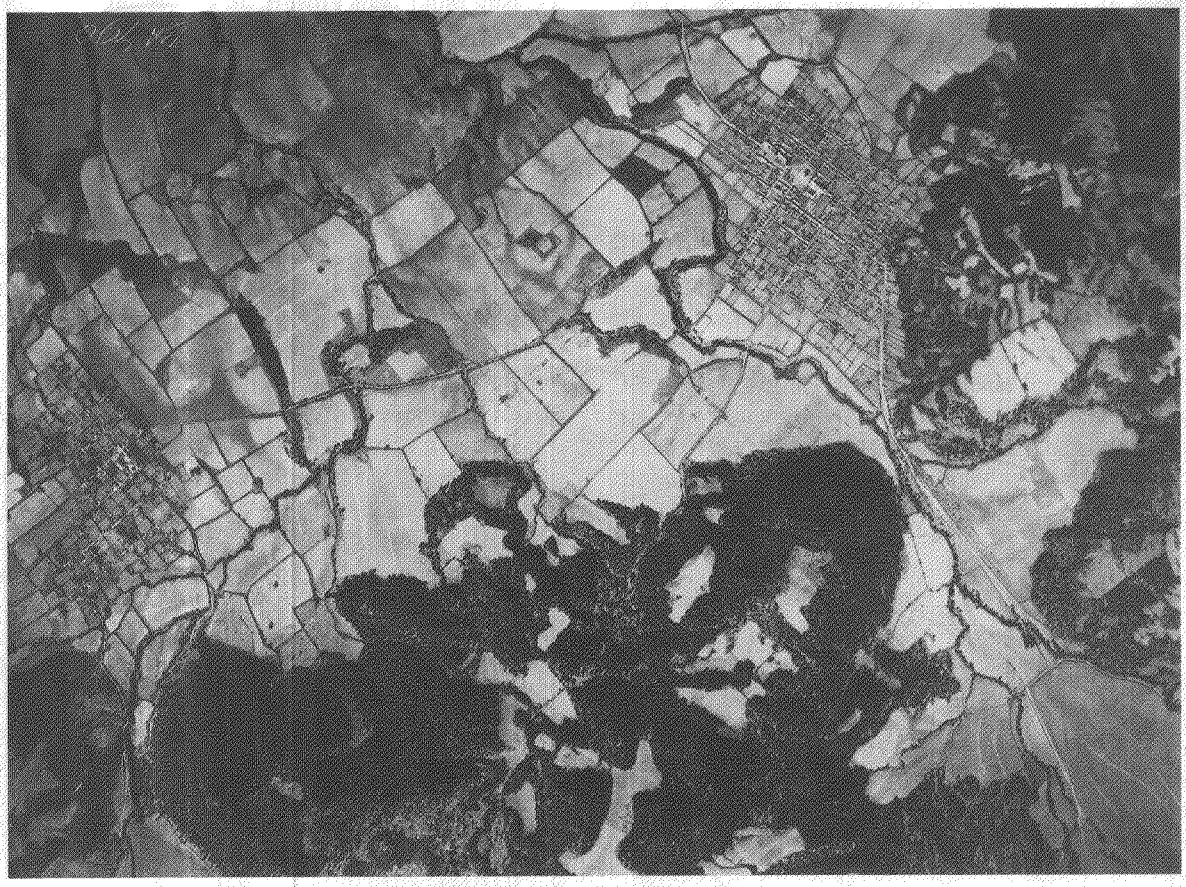


Fig. 2. Airphoto of the area in 1934, 9 years before eruption. The villages of Paricutin (left side) and San Juan Parangaricutiro (right side) were covered by lava and ash. Aerial photograph courtesy of Cia. Mexicana Aerofoto.

the altitude above mean sea level is 2820 m on the northwest point of the crater rim; the southeast point is 2817 m high. The cone basal diameter is elliptical, with a larger NW–SE axis 965 m in length and a NE–SE axis 620 m in length. The crater is centered slightly to the south on the large axis and is nearly circular in shape; the outer diameter is 262 m. As the lava flows covered the surroundings of the cone, the relative height and the apparent maximum diameter of the cone is less than it was in the first period of the eruption. The larger cone basal diameter in 1944 was 1100 m and the crater diameter 400 m (Segerstrom, 1950). The present dimension is similar but slightly smaller than that measured in 1954: 275 m (Foshag and Gonzalez, 1956). The calculated volume of the cone from the former ground is 0.14 km^3. The crater itself is divided into two vents by active slumps and its maximum depth is 42 m; the crater walls are 32° on the gentle slopes and 40° and above in the steep walls (Fig. 3). Major morphological features shown in the 1965 photograph of the interior of the crater (Segerstrom, 1966) were identified in 1990 (Fig. 4). The crater depth decreased since 1957 from 50 m to around 40 m due to filling by slides and rock falling from the rim and crater walls. Some areas of the substrate in the crater area are characterized by high temperatures and fumaroles, due to steam emission of meteoric water. The major change in the crater is the rapid revegetation in recent years. Early works by Beaman (1960) and Eggler (1959, 1963) describe mainly mosses, and one pine tree (*Pinus montezumae*)

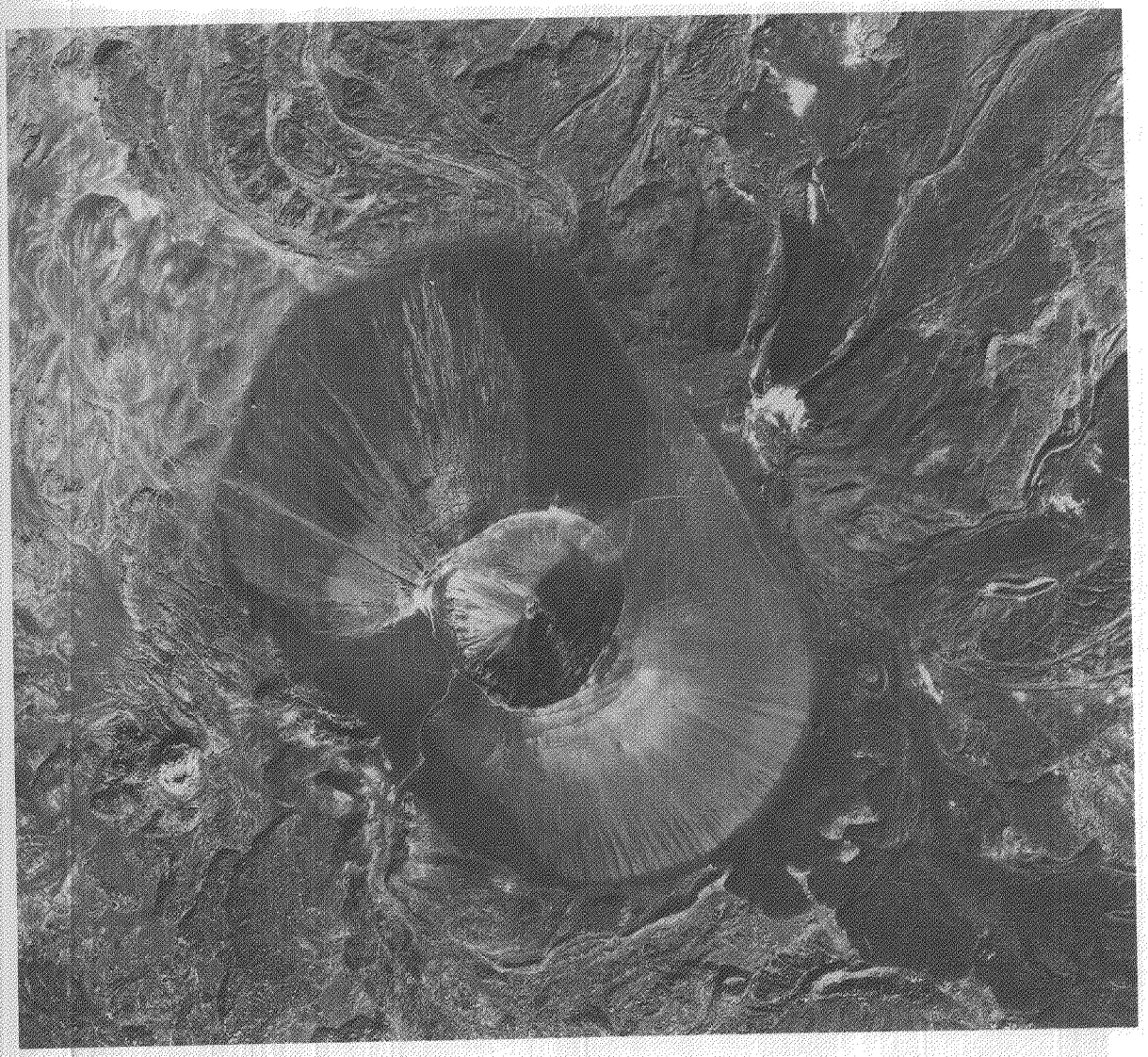
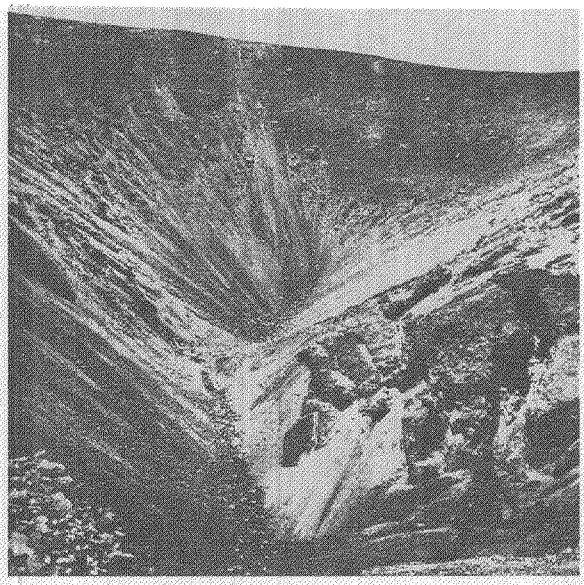


Fig. 3. Airphoto of Paricutin crater and cone, 1985. Long axis of cone is 965 m and crater diameter 260 m. Aerial photograph courtesy of Cia. Mexicana Aerofoto.

was then found. In 1990 vegetation was found according to the exposure on the north facing slopes; on the northeast facing slope, on a coarse scoria substrate, most of the vegetation are mosses, *Anobryum filiforme var. mexicana*, and one vascular plant, *Gaultheria hartwegiana spp. scrabrescens*. On the northwest facing slope, on a blocky substrate, a large number of pines (*Pinus leiophylla*) were found: on a 500 m^2 area 23 pines were counted and measured, most of them between 0.5 to 1.8 m high, with the largest reaching 3.0 m. Around the pines several plants from different families were found: gramineae — genus *Muhlenbergia minutiflora*, compositae — genus *Eupatorium*. In 1987 only a few trees were noticed; the fast development of vegetation between 1987 and 1990 is explained by the accumulation of weathered material in the inner wall and decrease of slope angles on the growing sites (Fig. 5).



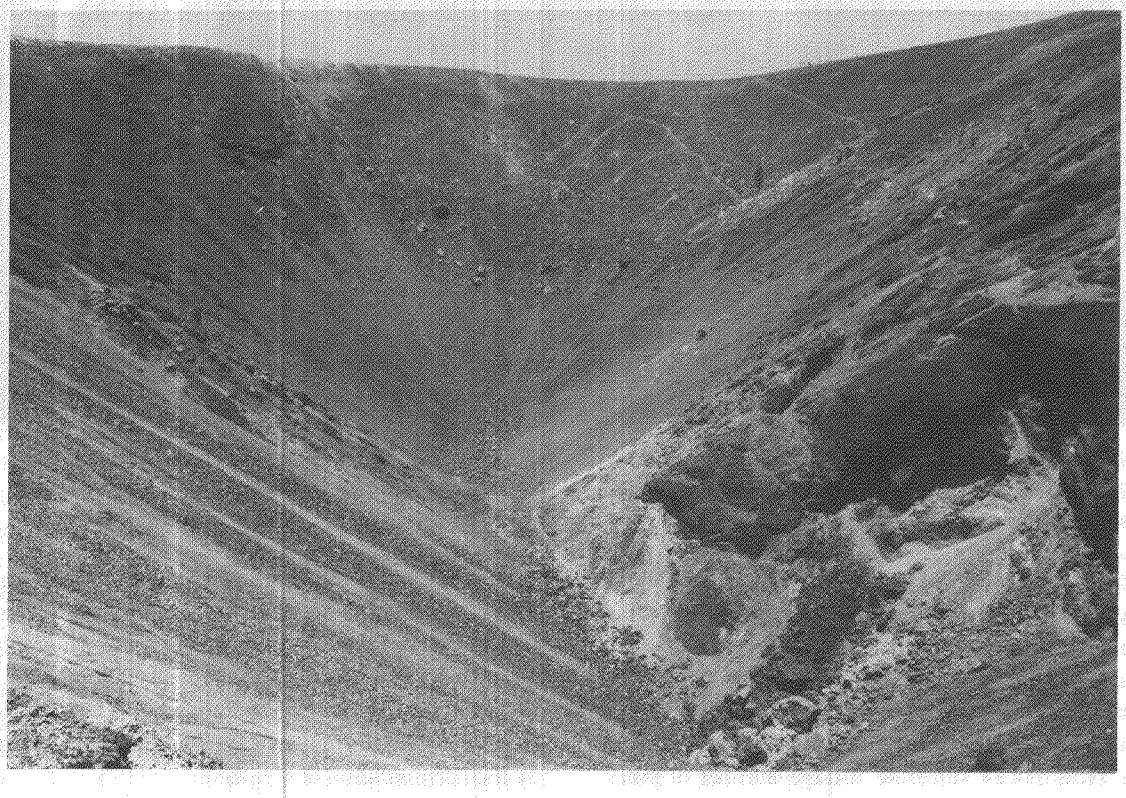


Fig. 4. Interior of Paricutin crater from southwest rim, showing two vents; top: 1965, taken by Segerstrom; bottom: 1990, with several pine trees in the upper right corner.

Fig. 5. Pines up to 3 m high in the southeast inner wall of the crater.

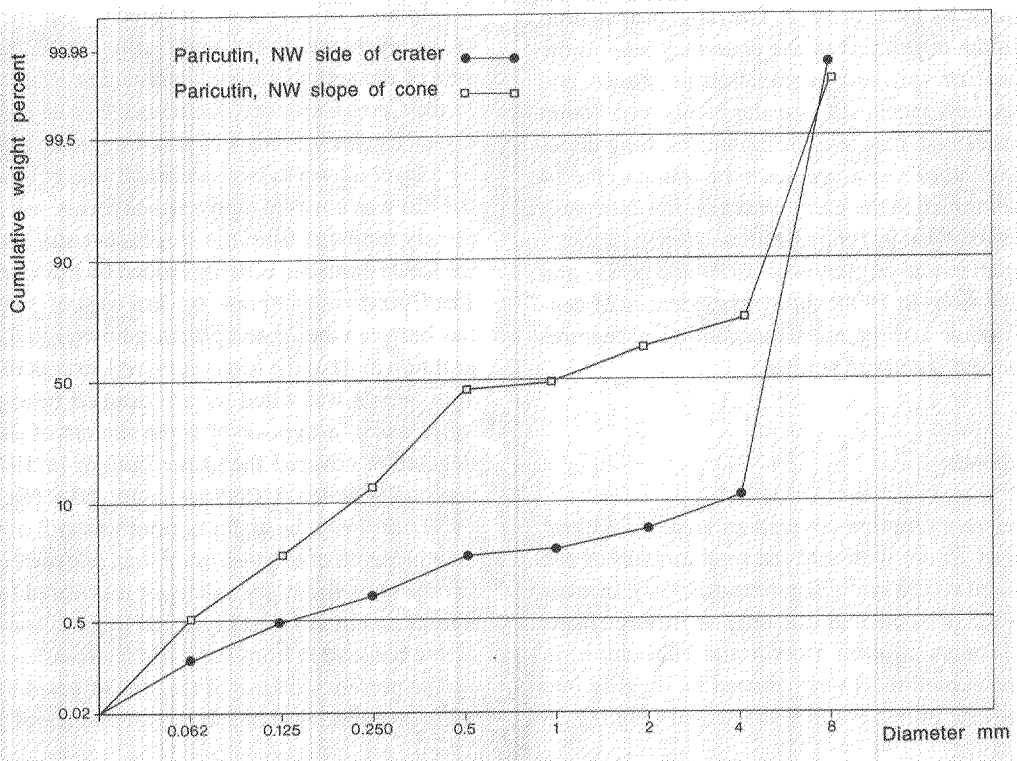


Fig. 6. Size distribution of tephra from the western side of the cone.

l pine trees

The angles of the outer slopes of the cone, measured from Cerro Capatzun, are 32°W and 31°E, similar to that measured in 1947: 31° to 33° (Segerstrom, 1950). The fine ash that covered the cone and a wide area surrounding it (Segerstrom, 1950) had disappeared. In 1972, during a first visit by one of the authors (M. Inbar), there was still a thin layer of fine ash, but almost no remains of it were found in 1987. The present lithological composition of the cone pyroclastic material is coarse ash and lapilli (Fig. 6). Fine particles are removed by wind action. In the lower part some rills are found with a larger concentration of plants indicating fluvial erosion, but most of the cone slopes are undissected. A major linear trench across one of the flanks is a man made sliding path. All rainwater infiltrates, as observed in many cinder cones the world over (Inbar, 1970; Ollier, 1988). The lapilli fans on the cone slopes described by Segerstrom (1960, fig. 1) were stripped. Vegetation started to develop in the upper parts of the cone slopes, with a vegetation cover of about 50% in the upper 50 m of the cone. The northern flank is completely covered by vegetation. The variety of species is greater than in the crater, with several kinds of trees, shrubs and grass. Beaman (1960) did not find any plants on the cone in 1958, and the same observation was made by Inbar in 1972. The rapid propagation of herbs in the upper part of the cone may lead to the development of soil and propagation of shrubs and trees. Three new species of vascular plants were found on the cone flanks, plus 5 in the crater, reaching therefore the number of 8 new species to be added to the 14 already mentioned in the early works on the cone vegetation (Eggler, 1959, 1963; Beaman, 1960).

A comparison of airphotos of 1970 and 1985, and field observations in 1990, show no evidences of centripetal drainage and the main morphological features of the cone and crater are similar.

5. Ash deposits

The Paricutin eruption covered an area of 233 km^2 to a depth of 25 cm with ash; the total amount of ash was estimated at 0.38 km^3 (Segerstrom, 1950). In areas within the 0.5 m isopach of ash, only shoveling efforts made by farmers allowed growth and cultivation. In other areas orchard trees were planted by digging into the ash until the previous soil was reached (Fig. 7). In 1990, all the areas behind the 1947 1 m isopach of ash are cultivated or covered with vegetation (Fig. 1). Revegetation, runoff and drainage development is faster in the shallow ash-covered area where the former soil influences plant growing. In areas where the ash cover was deeper than one meter, small sand dunes were formed and less vegetation developed. The present process is a rapid entrenchment and enlargement of the channels and deposition of the removed ash in the floodplains. In steep areas covered by ash, the stripping of the layers was faster, uncovering the old soil. Exposure of old soil was already noticed in 1950 in the area of the Cerro Capatzun, 3 km northeast of the Paricutin cone (Eggler, 1959). In 1945 Capatzun was covered by a layer of one to two meters of ash; in 1990 most of the hill was covered with a dense forest, ash was completely removed from the slopes, but still remained in the lower parts and is being eroded by fluvial processes. The Cutzato cinder cone, 6.5 km west of the Paricutin, lies between the 25 and 50 cm ash isopach. During the eruption most of the forest survived, except in the crater area, which was filled by ash drained from the crater inner walls; a deposit of three meters of ash free of vegetation covered the crater bottom in 1946, which seasonally holds a shallow crater lake (Segerstrom, 1950). In 1990 the crater bottom was still unvegetated and the depth of ash was more than one meter (Fig. 8). On the cone flanks the ash layer is covered by a recent humus and litter forest layer, but in the rills most of the active bedload is from Paricutin sources.

The present land use of the area affected by a 30 cm thick or more layer of ash shows that about 5% of the

Table 1
Land use in the Paricutin area, between 1900 and 3000 m altitude (Source: "El Comunero" 28 Nov. 1989)

Land use	Area (ha)
Commercial forest	10,652
Nature reserve forest	348
Agricultural cropland	3448
Orchards	1214
Bushes	259
Grassland	24
Volcanic sand area	443
Lava fields	1810
Total	18,198

Fig. 7. Planting tree in a 90 cm digged hole into Paricutin ash.

Fig. 8. Bottom crater of Cutzato cone, filled with Paricutin ash.

area is still covered by unvegetated or uncultivated ash (Table 1). Most of these fields were originally covered by 50 cm or more of ash on flat areas or gentle slopes and were not stripped by erosional processes.

6. Lava flows

Lava flows from the Paricutin are basaltic andesite rocks of the Aa type, usually blocky and highly vesicular. The porosity was estimated as 50% by Foshag (1950) and 30% by Fries (1953). The extent of the presently exposed flows is about 24.8 km^2, emitted during the nine years of volcanic activity. Most of the lava eruptions occurred between November 1943 and February 1944, about one year after the start of the eruption; the largest was the San Juan lava flow, which was emitted in June 1943 and followed a circuitous course of 10 km (Segerstrom, 1950). Several individual flows can be identified in the January 1985 airphoto, but it is difficult to map them since they are superimposed upon one another (Fig. 9).

The surface is hummocky with deep crevasses, some of them more than 5 m in depth; walking across the lava fields is still a difficult task. There is no surface drainage and rainwater infiltrates down the lava surface, forming a local aquifer that drains through several springs. Hot spots still existed in 1965 at the surface of the flows (Segerstrom, 1966); no vapor columns or fumaroles were distinguished since 1987 and 1990 on the lava fields.

The roughness and absence of homogeneity of the lava surface is characteristic of all lava flows, and in a detailed study of the San Juan 1943–1944 lava flow, several micro-terrain elements were distinguished: The flow is several hundred meters wide and diverted in two main lobes — to the north and west — about two km in length (Fig. 10). The following units were found in the central area of the lava field on the 1943 flow:

1. Rough terrain with large blocks

This zone is primarily composed of blocks larger than one meter, arranged in ridges with very steep walls. On the airphoto a clear linear pattern can be discerned. It covers about 2/3 of the lava flow . Deep crevices, four to five meters in depth are perpendicular to flow direction. The size of the lava blocks determine different levels in the rough terrain (Fig. 11). Lichens cover between 50 to 80% of the rock surface; vesicular rocks are covered with a more dense population of lichens and mosses.

Weathering processes were more developed in the rocks covered by lichens. No relationship was found between lichens or other vegetation cover and the terrain angle of exposure.

2. Blocky lava terrain

This area is identified as having a smooth surface on the airphoto; on the field the area is characterized by lava blocks, less than one meter in size, with deep crevices along them. There is no clear arrangement of the depressions and their depth varies from one to five meters. The size of the blocks was probably determined by plastic flow which ruptured the main flow. The mean elevation is lower than the former unit; the average slope of the lava fields is less than 1% and these areas will develop into depositional environments.

3. Crevices or trenches in the lava fields

This is the most active unit in the aa lava field, composed of the large crevices parallel or perpendicular to the main lava flow, and small cavities are found without any regular pattern between the individual basaltic blocks; the main crevices are four to five meters deep, and the deepest measured cavities reach six and a half meters. There is no drainage connection between the trenches and each one constitutes an independent drainage unit. The depression ground is filled with fine ash and an aeolic sediment washed down by rains from the upper layers; the depth of the accumulated sediment varies from a few centimeters to more than half a meter. Accumulation of fine material and vegetation development was observed in the first years after the eruption (Eggler, 1959), and was one of the first sites of plant growth in the volcanic area. Density of vegetation was between 10 to 30% for vascular plants in the depressions for three different plots, 1000 to 2500 m^2 each, measured in 1990. In each plot, one pine and 40 to 60 shrubs were found (Fig. 12). A vertical stratification of plants was noticed: the vascular plants are in the depressions and below them a cover layer of mosses and ferns. The recorded species in the study plots were: *Pinus leiophylla*, *Wigardia caracasana*, *Buddleia cordata* (trees), *Baccharis heterophylla* (shrub) and *Gnaphalium semilanatum*.

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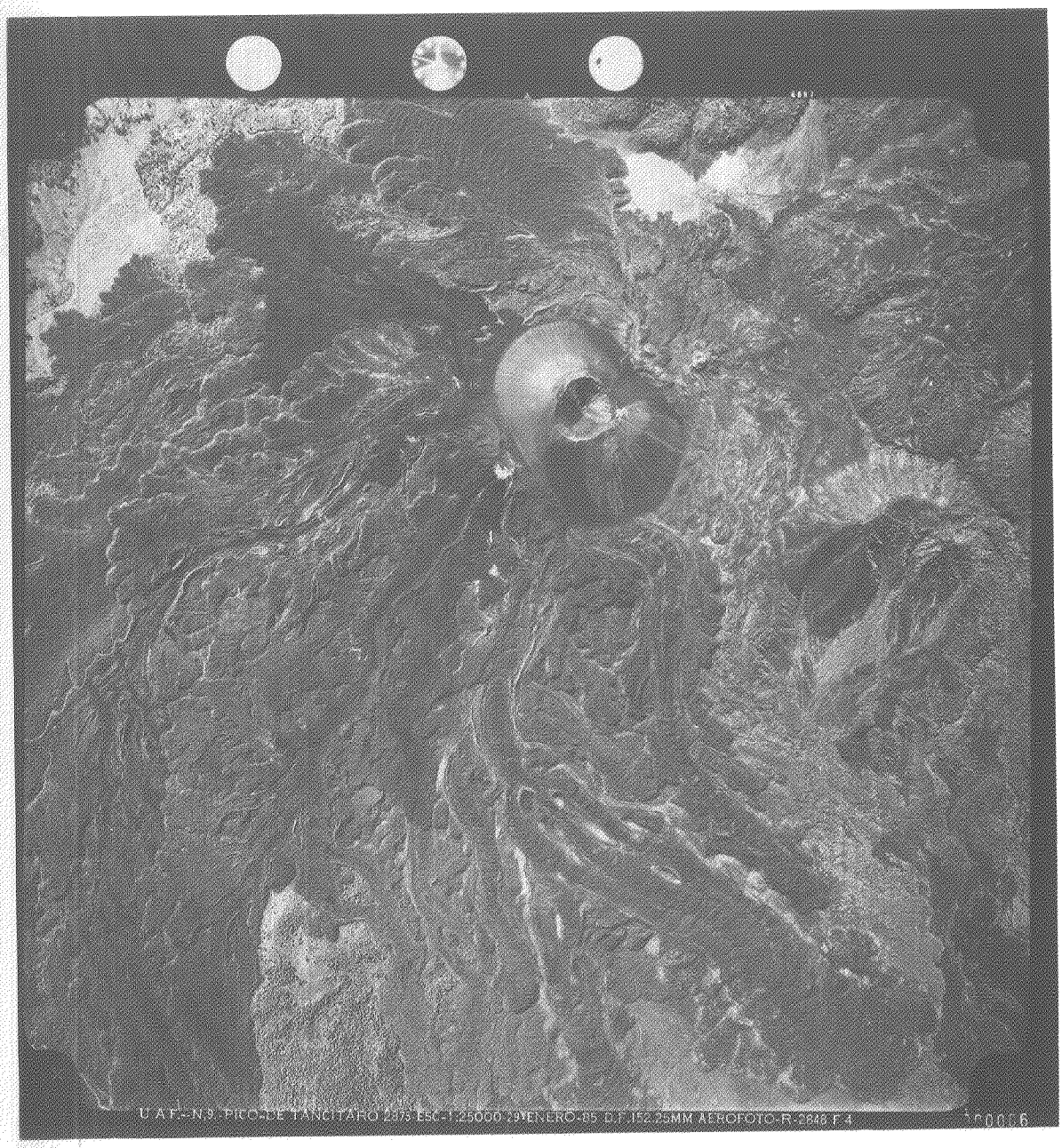


Fig. 9. Paricutin cone and lava field, 1985.

4. Front of lava flow

The largest lava stream, the San Juan flow, was an active flow during eight months, from 1943 until 1944. Most of the flow was covered by later lava flows, but the northern parts remained exposed (Segerstrom, 1950). The flow encircled several areas, and its front has a large perimeter. The lava front is an area of drainage and accumulation of sediments and vegetation cover. Most of the lava borders were covered by plants in 1990 and active processes of weathering, soil devel-

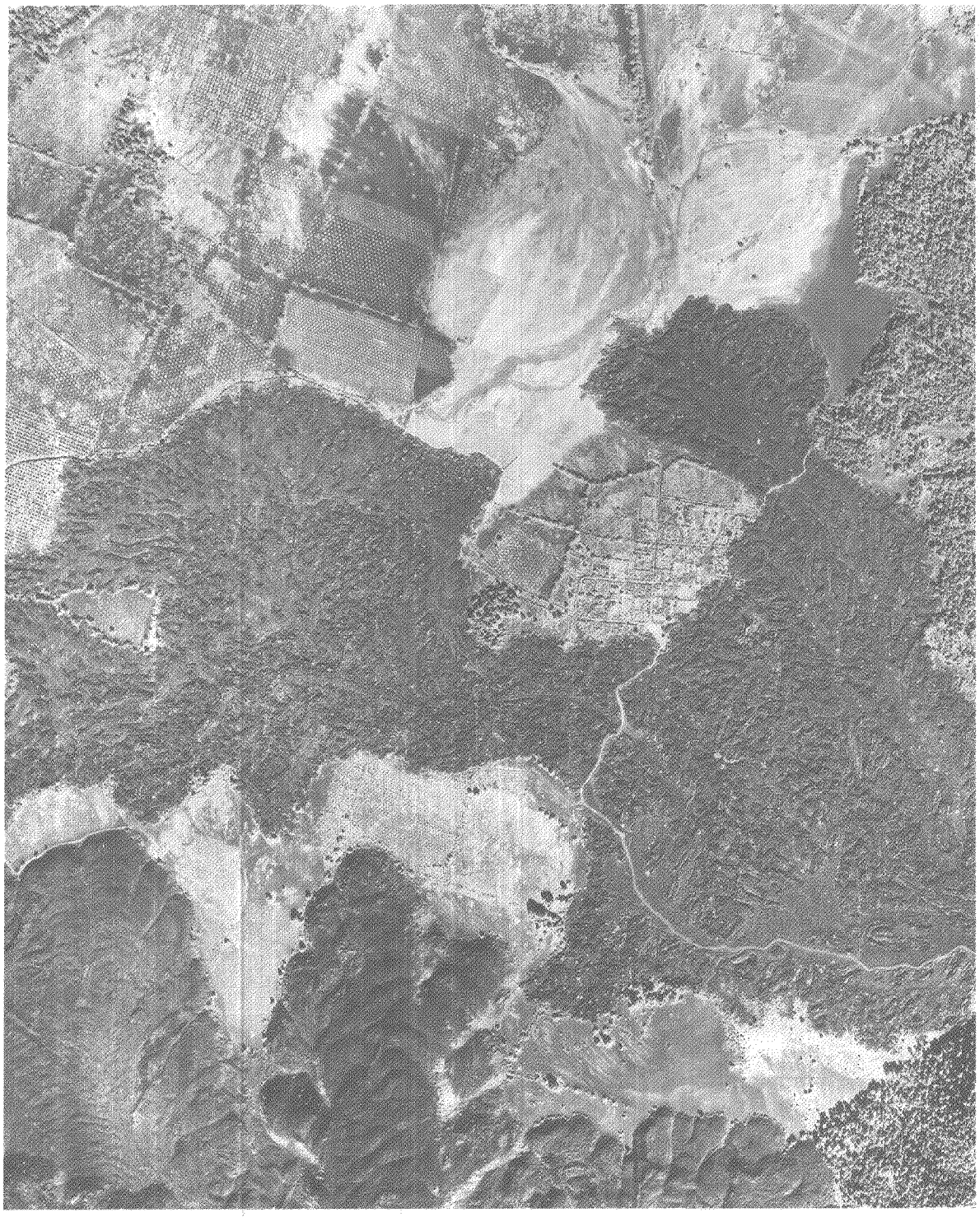
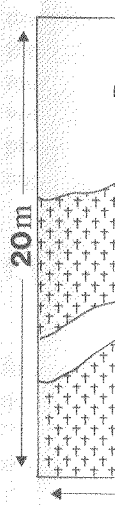


Fig. 10. Airphoto of the northern edge of the San Juan lava flow, 1985. Fields of the former village of San Juan and the Llano Grande in the upper part. Aerial photographs courtesy of Cia. Mexicana Aerofoto.



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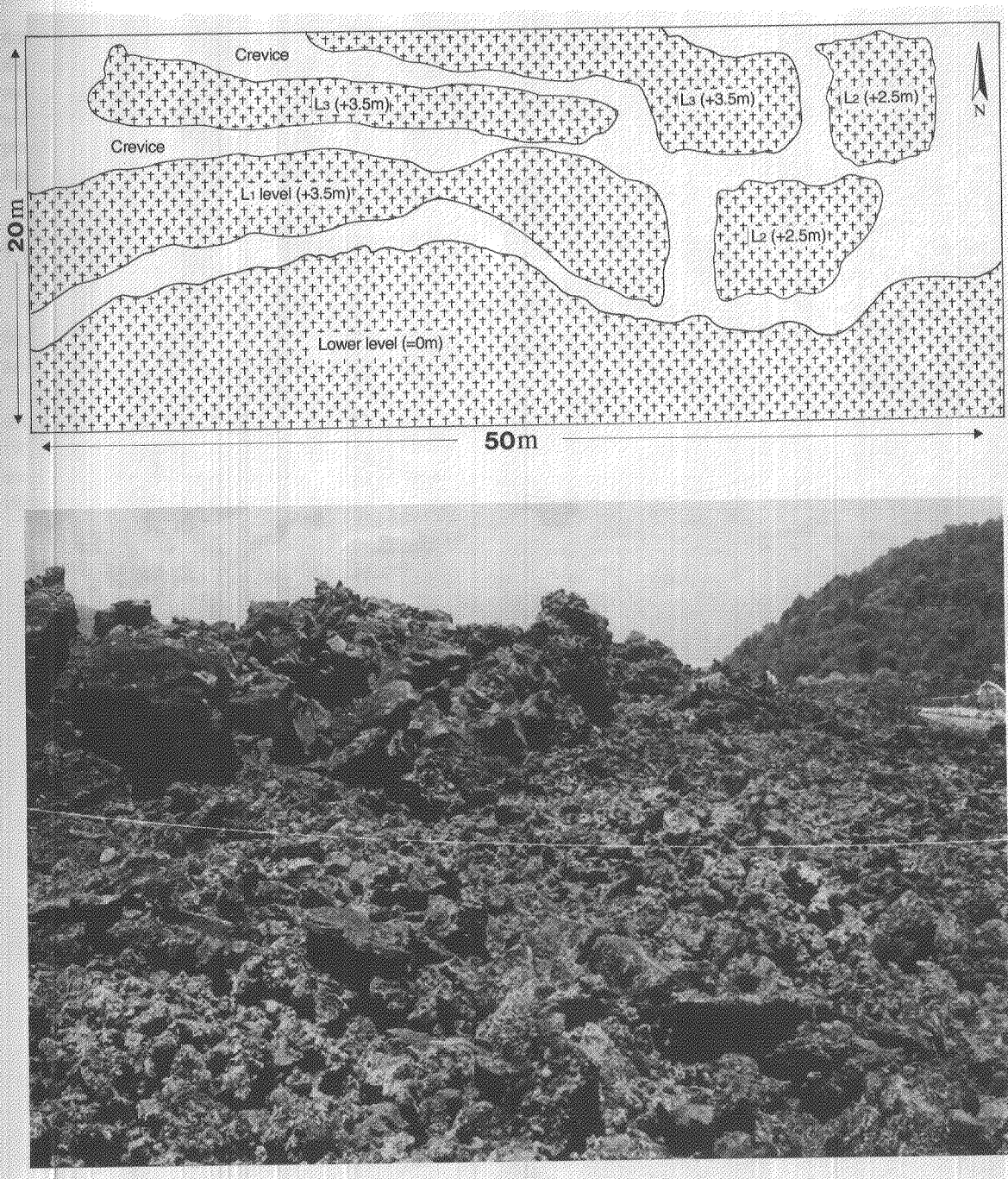

Fig. 11. Planimetric view and view of a blocky lava field.

opment and drainage integration were observed along the lava front edges. Vegetation is concentrated at the base of the lava front, where moist conditions prevail during most of the year (Fig. 13). The ratio of flow area (A) to flow perimeter (P) (A/P) for the San Juan flow is 0.15, lower than for other flows, indicating that

o Grande in the

Fig. 12. Vegetation in a lava field crevice.

Fig. 13. Front of lava flow. Vegetation develops along the edge of lava flow and corn is cultivated in the Curupichu llano; the Paricutin cone is seen behind the lava flow.

drainage development and morphological evolution of the area will be relatively fast. Under similar geologic, morphological and climatic environments the A/P ratio will be the major factor affecting the rate of geomorphological development of the different areas of the region. (Dohrenwend et al., 1987).

7. Floodplains (llanos)

The floodplains, or llanos as they called by the local farmers, are lava dammed plains draining former or newly developed streams. They were defined as "ponded areas associated with the lava field" by Segerstrom (1966), and called "playas" by Eggler (1948, 1959) who described the early vegetation of these areas. They developed around the lava fields and in 1985 covered an area of 5.06 km^2 (Fig. 14). The distribution of the "llanos" around the lava field indicates that most of them are in the eastern part of the lava field; the pre-eruption drainage was to the west, therefore the western tributaries were not blocked and small western areas drain into the lava field. The average area of the "llanos" is 0.5 km^2 (Table 2), and the largest is the Llano Grande, with an area of 2.48 km^2. The volcanically ejected rocks and ash raised the topographic level by 400 m in the cone area to about 10 m at the edge of the peripherial lava flows, changing therefore the previous drainage system and forming a local divide area. Most of the pre-eruption area was drained by the Itzicuaro river; lava flows blocked the upper tributaries of the Itzicuaro river, filtered the ash loaded waters forming large sedimentation ponds. Most of the deposition took place in the first years after eruption; a 5 m layer was deposited in the early stage in the Llano del Cantero. In the Cocjarao area, southwest of the

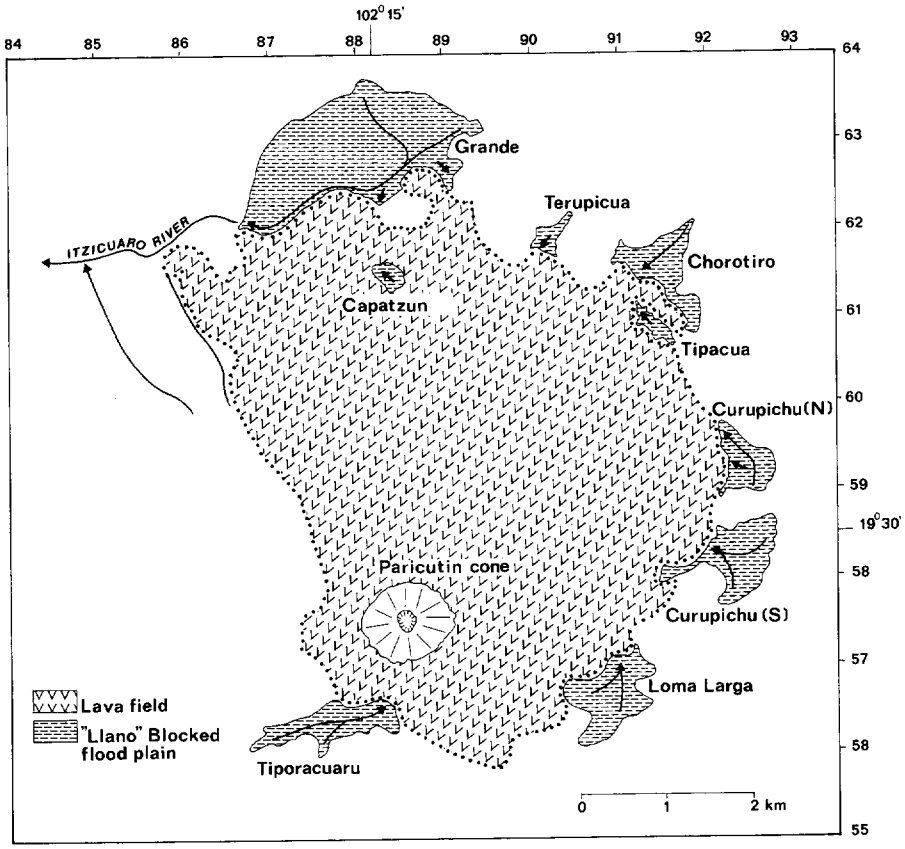

Fig. 14. Map of "llanos", developed in lava blocked floodplains of channels around the lava field.

Table 2
Area of "Llanos" (location in Fig. 14)

Name	Area (km^2)
Grande	2.48
Chorotiro	0 43
Terupicua	0.08
Capatzun	0.06
Tipacua	0.06
Curupichu (N)	0.31
Curupichu (S)	0.57
Loma Larga	0.62
Tiporacuaru	0.44
Total	5.05

Paricutin cone, the floodplain level rose by 40 m due to deposition. The first agricultural activity in the volcanic affected area was developed in the "llanos", and most of them were cultivated in 1965 (Segerstrom, 1966). Flooding and sedimentation was noted in several eastern llanos in 1987, and in the small floodplain formed by the Nureto river a pole fence built in 1980 was covered by sediments 20 cm in depth. Airphotos and field evidence show that in 1990 the "llanos" are still flooded periodically and silted by sediments deposited by the waters flowing into the lava field. As in alluvial fans, there is a decrease in particle size between the upstream and downstream areas of the "llano". Sediments are coarse, in the channels with median particle size in Arroyo Hurengo in the 16–32 mm range. In the floodplain the size of the sediment is smaller, in the range of median sand (Fig. 15).

The Llano Grande drains an area of 11.3 km^2 by two streams — Arroyo Hurengo and Arroyo Curitzeran — which are drained to the main Itzicuaro river. During high flows both streams drain into the lava field, but most of the channel flow is integrated into the main stream. The area of the llano is about 95% vegetated mainly by orchards; the depositional area of the streams and the area covered by coarse ash particles are without vegetation. The Tipacua Llano has an area of 0.063 km^2 and is not cultivated, probably for economic reasons, because flooding problems were already solved in the early sixties (Segerstrom, 1966); a dense natural vegetation reaching a height of 4 m is found around the edges of the lava front, covering 42% of the "llano" area and indicating a higher content of moisture and clay and silt particles in the soil. The flooded area is composed of gravels and coarse particles and covers 24% of the "llano"; the sediment filling is several meters deep (Fig. 16).

8. Drainage development

Before the eruption, the area drained to the west toward the Itzicuaro river; from the 1934 airphoto (Fig. 2), a pre-eruption drainage map was drawn by Segerstrom (1950), showing that except for a small local pond, La Lagunita (close to the former village of San Juan), there were no internal drainage systems in the area. After the eruption the main lava field and all the blocked streams had no external drainage, creating an endorreic system that covers about 160 sq km and flows into the lava field. The divide of the endorreic system is close to the western edge of the lava field, but to the north, south and east it included all the drainage areas of the dammed rivers by the lava field (Segerstrom, 1950). Since the drainage divide map drawn after the 1946 airphoto, the only major change observed was at the northern edge of the lava field, where there has been a partial integration of the Hurengo and Curitzeran streams, draining 15 km^2 toward the Itzicuaro River. The Itzicuaro river is 150 m lower than the eastern edge of the lava field, and a further incision of the channels around the lava field will integrate most of the blocked drainage system into the main external drainage. Around the lava field edge, new channels incised into the "llano" sediments are developing.

The large amount of water drained into the lava fields raised the groundwater aquifer which is drained by several springs in the western area of the region, such as the springs of Sipicha, increasing their discharge by more than 50% during the period 1946–1957 (Segerstrom, 1966).

9. Discussion

In 1990, after a period of 47 years of the beginning of the eruption and 38 years after cessation of the volcanic activity, Paricutin may still be considered an advantageous natural laboratory for the study of the recovery and geomorphic development of recent volcanic landforms. Three main periods of erosion were

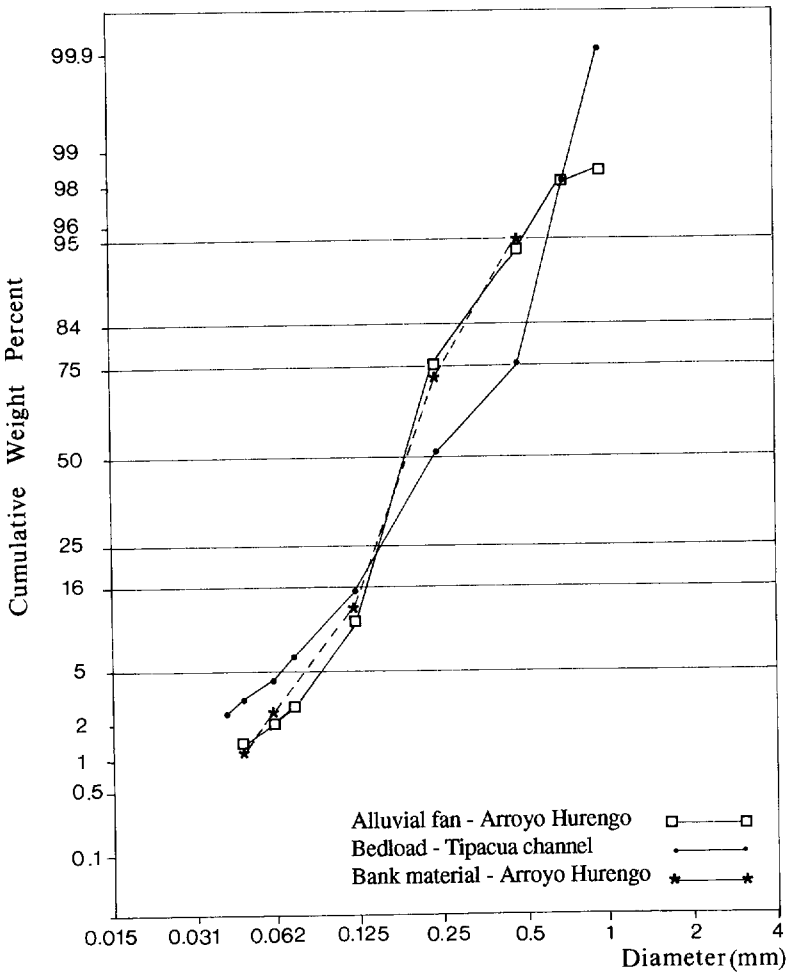

Fig. 15. Size distribution of bedload — Hurengo channel.

distinguished by Segerstrom (1961): (a) Between the beginning of the eruption in 1943 and the end of the rain period of 1944; this is the stage of accelerated erosion, with the stripping of the ash layers from the unvegetated affected areas by the eruption. Sediment yield and rates of erosion were three or four orders of magnitude higher than the normal rates. Peaks of erosion in this first stage of one or two years were recorded in several volcanic areas of the world (Swanson et al., 1983; Collins and Dunne, 1986). (b) Between 1944 and 1952, the end of eruption; this is a deceleration period, due to the decrease in the rate of pyroclastic material eruption, revegetation in the areas covered with a thin layer of ash, increase of infiltration in the new ash layers and development of a new drainage system. In this period rates of erosion are one or two orders of magnitude larger than normal rates. (c) The post eruption period, until 1970, with a gradient deceleration in erosion rates until they reach the normal values for the area. Unlike Segerstrom's graph (1961) showing a total recovery and normal rates of erosion by 1980, the present situation is that erosion rates are about 50% above normal, as exemplified by silting rate in the llanos (Fig. 17). The trend in the next period, after 50 year of eruption, will be of slower rates of erosion and may extend over decades or centuries until a complete rehabilitation of the area, depending on the different physiographic units of the area (Fig. 15):

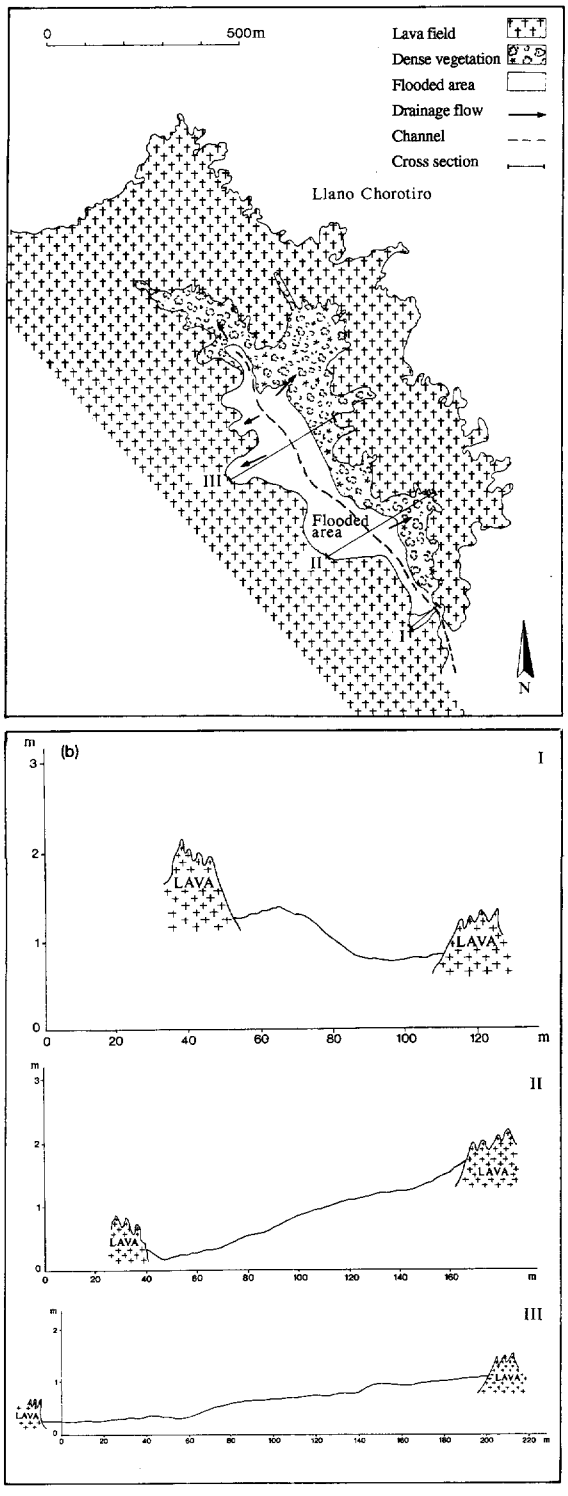

Fig. 16. Llano Tipacua — physiographic units and transversal cross sections.

1. *Cone and crater*: After the first stage of stripping of fine ash, erosion processes are slow, and the main development is the vegetation cover; the decrease in erosion rates is due to the initial stripping process and increase of infiltration, similar to the evidences found in Mount St. Helens (Collins and Dunne, 1986). The Jorullo cinder cone, 72 km southeast of the Paricutin cone which erupted in 1759, was already vegetated about 100 years after eruption (Segerstrom, 1950). In 1990 the Jorullo cone and crater were completely covered with a dense vegetation, controlled mainly by fire and human exploitation; climatic conditions are drier and warmer in the Jorullo area, but it seems that the rate of revegetation will be similar for the Paricutin cone.

2. *Ash covered area*: All of the ash layers deposited in the Paricutin area, including those within the one meter isopach of ash, have been subjected to some erosional processes since the eruption; wind was an important agent in the first stage, but water is now the main erosional agent. Fine material is redeposited by fluvial processes in the "llanos" or covered by vegetation and integrated in the soil profile. Coarse material fills the stream channels and in flat areas small sand dunes were formed. The factors affecting the stripping of the Paricutin ash were: thickness of the deposit, size of the materials, revegetation processes, morphological features and human interference which was a major factor in the affected agricultural areas. Similar conclusions were reached in the study of the tephra deposited by the Kilauea volcano after the 1790 eruption (Malin et al., 1983). It is worth noting that most of the craters within the 0.25 m ash isopach, at about 8 km distance of the Paricutin cone, are still covered with deep ash layers and unvegetated, keeping the ash deposits for a long term period as an exposed layer.

3. *Lava fields*: This is the area least affected by erosional processes and most of the flows have a fresh appearance after the 47 years period. Following Segerstrom's work (1950), observations were conducted in the Jorullo — 1759 eruption — and Ceboruco — 1870 eruption — lava fields. The Jorullo lava field is partially covered by vegetation, developing mainly in the crevices and depressions, but the Ceboruco lava flow has little vegetation cover and soil development. In Victoria, Australia, lava flows up to 20,000 years old have no soil (Ollier, 1988); for south-central Nevada rates of accretion of a mantle of silt and sand are more than

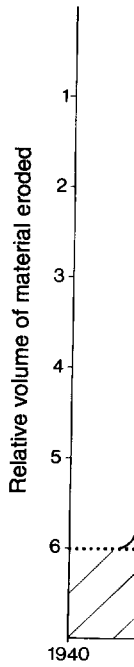

Fig. 17. Ero

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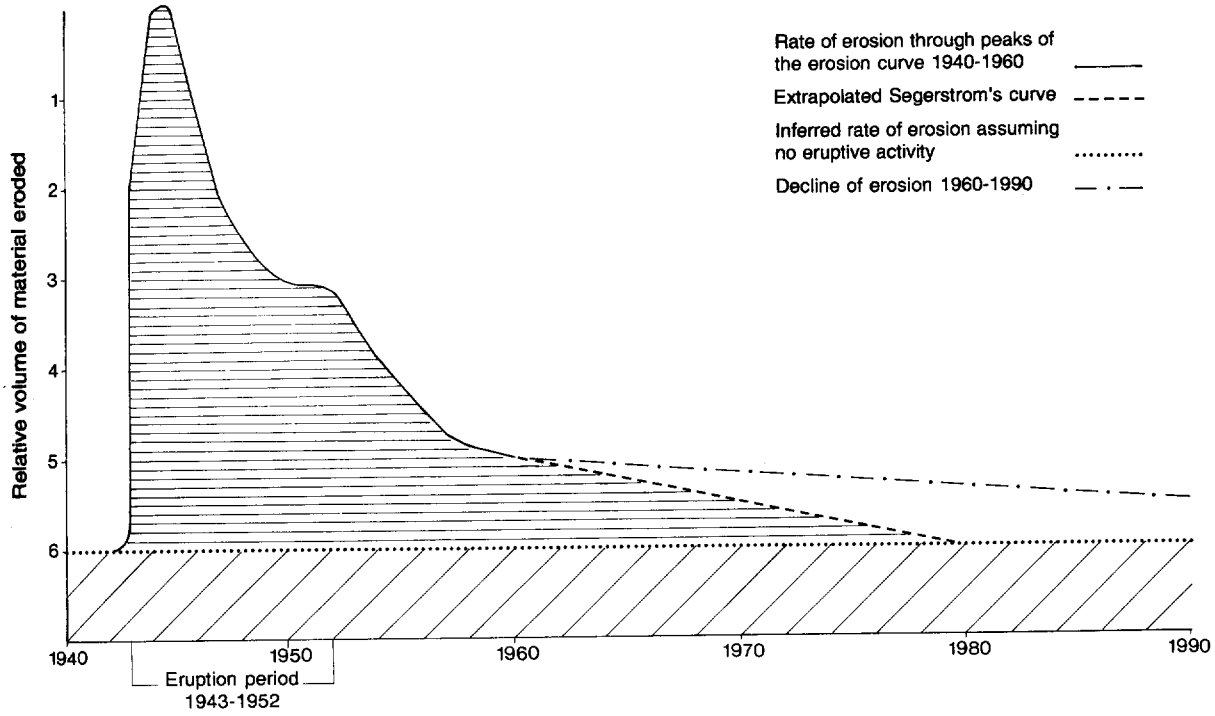

Fig. 17. Erosion rates at Paricutin during the period 1940–1960 (modified after Segerstrom, 1961) and trend for the 1960–1990 period.

100,000 years (Dohrenwend et al., 1987), and in Hawaii the 1790 Kilauea lava flow is still undrained (Malin et al., 1983). It seems that the revegetation, filling of sediments and weathering processes in the Paricutin area will develop in a shorter period, several centuries or a few millenia. Vegetation cover and drainage is more developed along the edges and on elongated flows with a low A/P ratio.

4. *Floodplains* (*Llanos*): In the post eruption period, this is the most active physiographic unit, and continuous floods during the rainy period add sediments to the llanos. The development of deep, incised channels along the edges of the lava field is noticed in some llanos, such as Llano Grande and Llano Curupichu, and the drainage system is partially integrated into the main Itzicuaro river. The floodplains areas are almost completely covered by vegetation or under agricultural use: these are the main factors affecting the morphological development of this unit.

Land, forest management and other human activities are presently major factors determining rates of erosion in the areas affected by the Paricutin eruption; the declining trend shown in Fig. 17 will probably continue for several decades until it reaches the normal erosion values for the area.

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