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GEOMORPHIC EFFECTS OF THE RETREAT OF JAMAPA GLACIER, PICO DE ORIZABA VOLCANO (MEXICO)

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ABSTRACT. Pico de Orizaba (5,700 m), on the eastern edge of the Transmexican Volcanic Belt, is an active volcano whose most recent eruption took place in 1687. Its summit is now covered by an ice cap from which several glaciers form. As on other mountains of central Mexico, the glaciers of Pico de Orizaba have retreated considerably during the past century and, in particular, during the last decades. This study focuses on the recent evolution of Jamapa Glacier, on the northern part of the mountain. It analyzes the geomorphologic processes in relation to the rapid retreat of the glacier snout and the intense periglacial activity on the valley sidewalls. The paper presents data on the thermic regime of ice cover deposits and their contrast with that of the glacier. At the end, it summarizes a model of the geomorphic evolution of the area below a retreating glacier.

Introduction

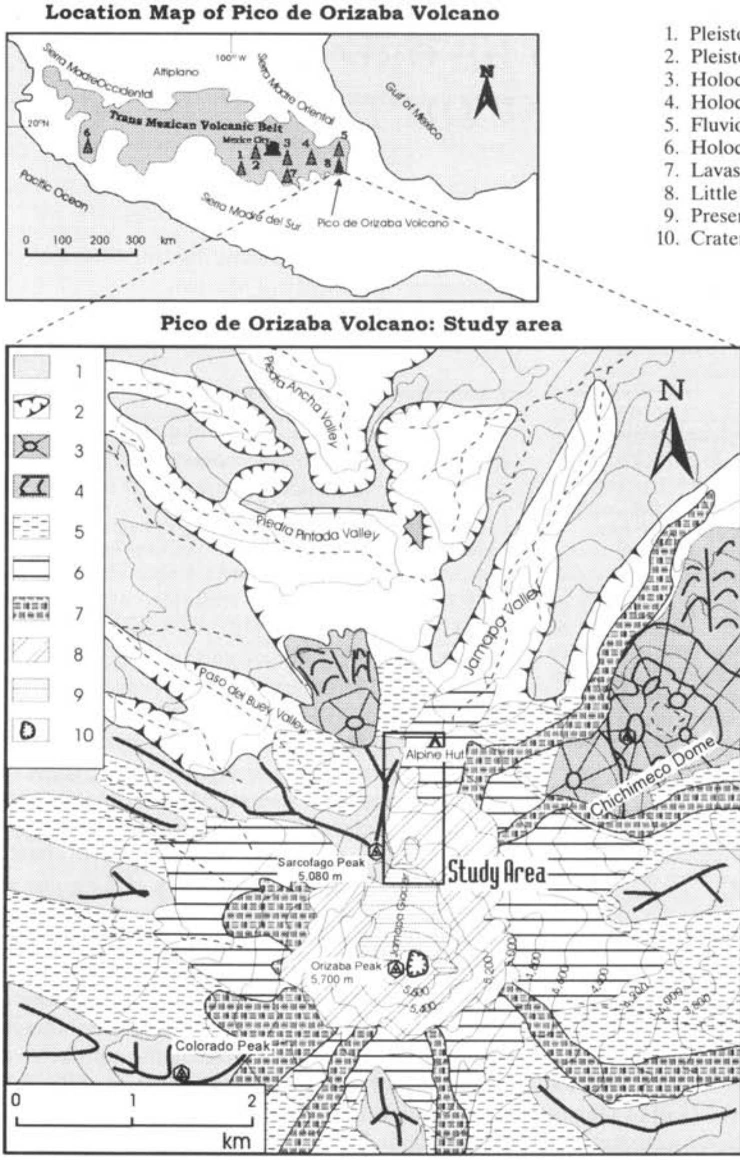
Pico de Orizaba volcano, also called Citlaltépetl, is on the eastern part of the Transmexican Volcanic Belt, at 19° 01' N and 97° 16' W, less than 100 kilometers west of the coast of the Gulf of Mexico (Fig. 1). Its altitude has never been accurately determined and current references range from 5,675 to 5,700 m. Pico de Orizaba is one of the three Mexican stratovolcanoes that still has glaciers. The other two volcanoes are Popocatépetl (5,450 m) and Iztaccíhuatl (5,286 m). Pico de Orizaba and Popocatépetl have had recent and also, present day volcanic activity, but it was mainly during the Recent Pleistocene and the Holocene that volcanic and glacier activity interacted. This has generated distinctive types of processes and landforms. During the last century the retreat of the glaciers became evident, and in the valleys and basins that were exposed after the ice withdrew, a peculiar type of erosive process took place that was conditioned mainly by the kind of volcanic rock found there.

Robin and Cantagrel (1982) defined the overall volcanic history of Pico de Orizaba. Robin, Cantagrel and Vicent (1983) Hoskuldsson and Robin (1993), Siebe *et al.* (1991, 1993) and Carrasco-Núñez *et al.* (1993) studied various eruptive events of the Late Pleistocene and Holocene in detail. Heine (1975a, 1988) identified several moraine complexes of the Late Pleistocene and Holocene on Pico de Orizaba and correlated them to those of other mountains of central Mexico. He also reported the presence of permafrost in the proximity of Jamapa Glacier (Heine 1975b). Lorenzo (1964) surveyed and mapped the glaciers of the volcano and made some observations on the youngest moraines.

This paper analyzes the geomorphic processes developed during past decades in the most important glacier valley of Pico de Orizaba: the Jamapa Valley. These processes are due to the rapid retreat of the glacier and to the characteristics of the volcanic materials. Local bibliography and aerial photographs from different periods were used to study the volcano-glacial evolution of Pico de Orizaba. Fieldwork carried out in February 1994 produced an accurate geomorphologic map and data on the sedimentary and thermic characteristics of the retreating glacier and derived deposits. On this basis a hypothesis was developed on the recent geomorphic evolution and the types of processes operating today.

Volcano-glacial context of the study area

Pico de Orizaba is on the eastern edge of the Trans-



1. Pleistocene volcanic ridge.
2. Pleistocene glacial valleys.
3. Holocene volcanic domes.
4. Holocene lava flows.
5. Fluvioglacial and volcanoclastic sediments.
6. Holocene maximum glacial advance.
7. Lavas from 1537–1687 eruptions.
8. Little Ice Age maximum glacial advance.
9. Present glacier.
10. Crater.

Fig. 1. (top) General location map. 1. Nevado de Toluca; 2. Ajusco; 3. Iztaccíhuatl; 4. Malinche; 5. Cofre de Perote; 6. Colima; 7. Popocatepetl; 8. Pico de Orizaba. (bottom) Pico de Orizaba Volcano

mexican Volcanic Belt. Its eastern slope has an extensive piedmont that grades into the coastal plains of the Gulf of Mexico. Its western slope, in contrast, ends in the plains of the Cuenca de Oriental, the southeastern part of the Central Mexican Highland (average altitude 2,200 m).

Pico de Orizaba forms the southern part of a North-South volcanic range of *ca*. 35 km long and steep asymmetrical slopes. Lithology is dominated by andesites and dacites (Rodríguez-Elizarrarás and Lozano 1991). Cofre de Perote (4,282 m), the northern point of the range, is an inactive stratovolcano with evidence of extensive glaciation probably dating from the Late Pleistocene. Xausta Dome (3,880 m), Las Cumbres Caldera (3,940 m) and several other mountains with altitudes over 3,800 m located between Cofre de Perote and Pico de Orizaba have similar morphologic evidence of glaciation.

The eruptive history of Pico de Orizaba has been divided in three stages (Robin and Cantagrel 1982). During the first one, which lasted 1 million years, the entire base of the stratovolcano developed. During the second stage (100,000 to *ca.* 33,000 yr BP) the formation of a large caldera was followed by large andesitic and dacitic domes and numerous blocks and ash flows (Robin and Cantagrel 1982; Hoskuldsson 1990; Hoskuldsson and Robin 1993). The third phase began 19,000 yr BP with the formation of the new cone, which covers most of the wall of the caldera and the inner domes. It consisted of several alternated phases of andesitic lava flows and pyroclastic eruptions (Hoskuldsson and Robin 1993). An episode of debris avalanche that was transformed into lahar, seemingly due to the presence of glacier ice took place at *ca.* 13,000 yr BP on the eastern slope (Carrasco-Núñez *et al.* 1993). A series of pyroclastic flows were channeled through a glacier cirque and formed a wide fan on the western slope between 4,660 and 4,040 yr BP (Siebe *et al.* 1993). The last eruptive phase (700 A.D. to 1687 A.D.) included seven separately identifiable eruptions. They were effusive, with the exception of one plinian event (Mooser *et al.* 1958; Simkin *et al.* 1981; Robin and Cantagrel 1982; Cantagrel *et al.* 1984; and Hoskuldsson and Robin 1993). The historic lavas were emitted from the upper crater and flowed down in all directions. They advanced through the ravines and glacier valleys and in some cases filled them completely. In 1537 the lava flowed on the north and northeastern sides, while in 1545, 1566 and 1613 it flowed on the south side. The activity continued until 1687 with weak explosive eruptions. Since then, there has only been mixed fumarole activity (Hoskuldsson and Robin 1993).

According to Heine (1975a, 1983, 1988) the maximum advance of the glaciers prior to the advent of Holocene conditions took place between 10,000 and 8,500 yr BP on Pico de Orizaba and in general in Mexico. He also identified signs of only two Neoglacial advances. The first one is evidenced by morainic loops around the base of the terminal cone at 4,000–4,400 m, which were deposited prior to 1730 ± 85 yr BP and probably between 3,000 and 2,000 yr BP (Heine 1983, 1988). The second Neoglacial advance is from the L.I.A. (Little Ice Age), which reached its limit of influence in Mexico by the middle of the 19th century and formed a series of moraines between 4,400 and 4,800 m on Pico de Orizaba (Heine 1975a, 1983, 1988). In both Neoglacial episodes, the glaciers extended mainly on the northern and western slopes.

It is interesting to point out that the end of the last eruptive episode coincided with the beginning of the L.I.A., so the eruptions would have destroyed the existing glaciers. Subsequently the glaciers of the L.I.A. formed on top of the new lava.

Geomorphology of the north face of Pico de Orizaba

A major feature of the northern slope of Pico de Orizaba is Sarcófago Peak (5,080 m), a remnant of an older cone which collapsed to the north (Hoskuldsson and Robin 1993) (Figs 2 and 3). A large amphitheater on the west side of the peak has been interpreted as the result of a more recent collapse (Hoskuldsson 1990; Hoskuldsson *et al.* 1990) and also as a glacial cirque which channeled a series of block and ash flows between 4,600 and 4,040 yr BP (Siebe *et al.* 1993). The eastern wall of Sarcófago exposes many andesitic lava flows interspersed with pyroclastic flow and fall deposits. It limits the north face of the modern terminal cone. A lava flow of large dimensions descends from the crater and covers nearly the entire north face of the cone. It is the youngest formation of the northern slope and has been related to the eruption of 1537 A.D. and called Jamapa Lava Flow by Hoskuldsson and Robin (1993). The lava moved from the crater and formed well developed levées. Its upper portion is concealed by an ice cap, whose longest snout is called Jamapa Glacier (Lorenzo 1964). The glacier now lies atop part of the lava, but during the L.I.A. it covered it completely (Figs 2 and 3).

The entire surface of the lava flow shows evidence of glacial abrasion. Above 4,500 m there are no remains of glacial sediments, but beyond this elevation the lava lies beneath various morainic formations that were earlier identified as belonging to the L.I.A. (Heine 1975a, 1983, 1988). During the main advance the morainic material accumulated along all of the frontal portion of Jamapa Glacier, except on the western margin where the glacier was confined by the wall of Sarcófago. Remains of the corresponding lateral moraine appear at an altitude of 4,737 m on the eastern margin of the former glacier tongue. The frontal moraine is better preserved. Its inner area is

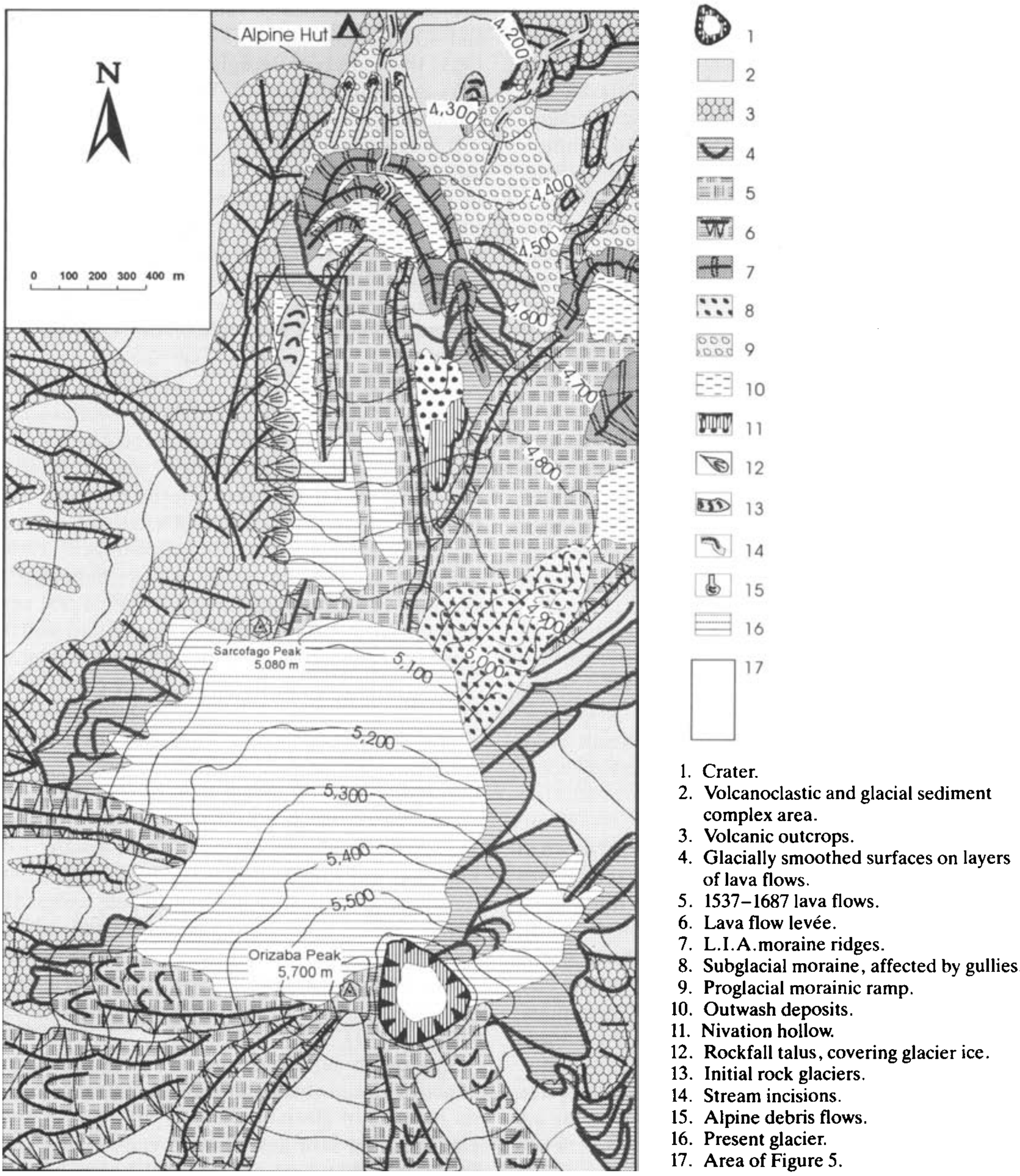


Fig. 2. Geomorphologic map of Jamapa area (North face of Pico de Orizaba volcano).

concave and includes a small terminal basin now opened by gully incision. The crest is well defined and its lowest elevation is at 4,395 m. This point marks the lowest level to which the glaciers on Pico de Orizaba advanced during the L.I.A. The outer portion of the morainic formation consists of a large ramp that reaches down to 4,200 m and was created by glacial pushing and the additional action of proglacial waters. Subsequently, intense alpine debris flow processes developed on top of the ramp. Following the debris flow stage, a gully incision process began that continues today.

Fig. 3. Block-diagram of upper Jamapa valley (North face of Pico de Orizaba volcano).

Almost parallel to the aforementioned morainic ridge is a second one with similar characteristics, but developed only in the central part (Figs 2 and 3). It indicates that the glacier front readvanced to an altitude of 4,460 m. A third ridge, smaller and located at higher elevation, is confined by the western levée of the large andesitic lava flow of 1537 and a prominent step formed on earlier lava flows. It suggests a third readvance of the glacier tongue that reached 4,485 m. These morainic ridges are composed of heterometric materials ranging from abundant great blocks (1.5 m in diameter) to fine particles, primarily ash. The central lava flow contributed little load to the glacier. According to a rough estimate, about two thirds of the fragments in the central part of the lowest ridge came from the walls of Sarcófago. Once the ice recedes from the base of the wall, a lot of material generated by erosion accumulates on the large taluses and traps glacial ice in their interior as discussed below (Heine 1975b).

Partially covered by this lava flow, is another flow located to the east, with similar lithologic and morphologic characteristics formed during the same eruption (Hoskuldsson and Robin 1993). It also has well developed levées and a gently sloping central surface that channeled the ice cap, creating a large glacier tongue during its farthest advance in the L.I.A. A large frontal morainic ridge is also visible here and ends in a wide outwash. The front of the ice cap is now found on the upper part of the lava flow (Fig. 2 and 3). In contrast to the north side, the retreat of the glacier has left a vast, thick layer of subglacial moraine on the lava flow. The surface of this layer has an irregular pattern of deformations and creates a series of small crests oriented in the direction of the flow. The deposits are heterometric, although there is a lot of fine material, mainly in the form of ash. Their origin could be linked to a pyroclastic layer now covered by the ice cap in higher slopes. In 1975 the interior of this moraine was frozen (Heine 1975b).

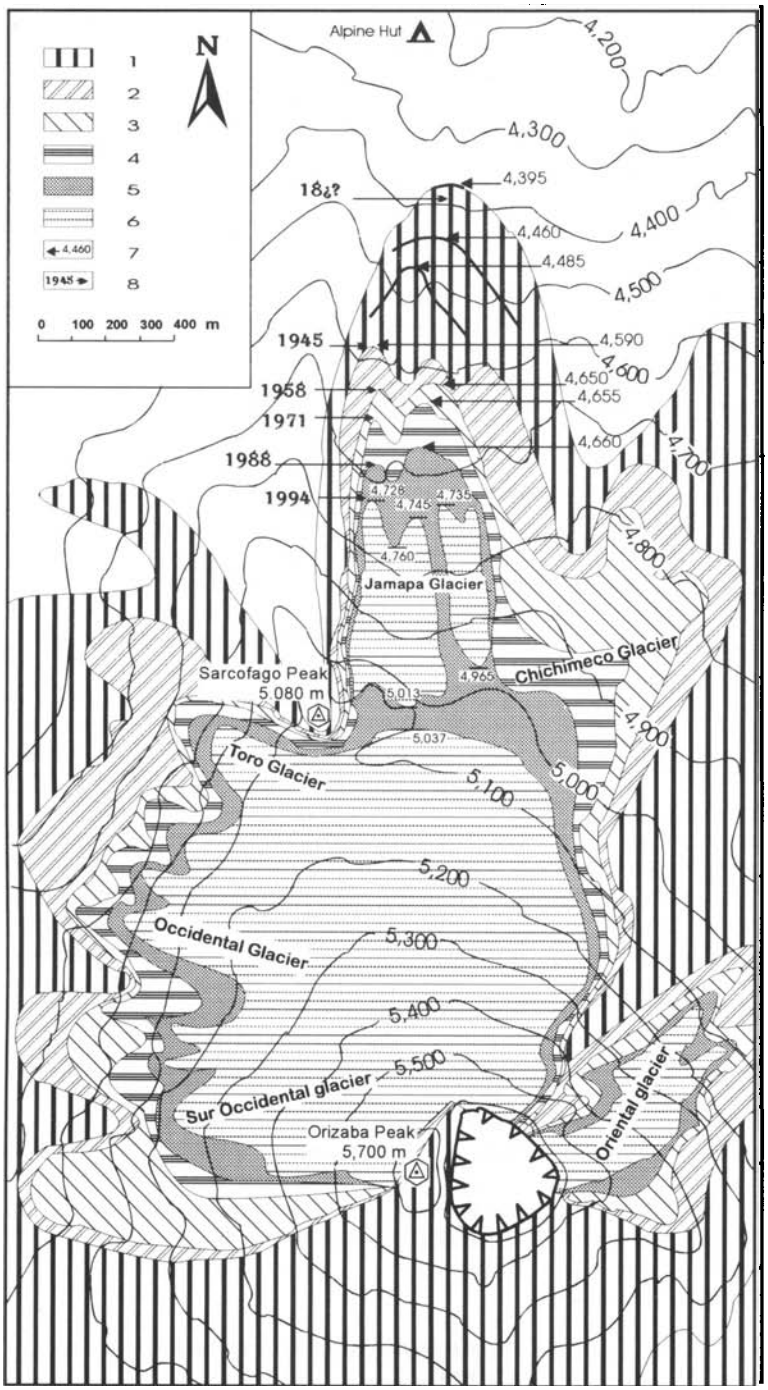
Between the levées of the two recent lava flows described above, there is a very noticeable nival hollow (Fig. 2). The floor of the hollow is strewn with blocks that have fallen from the walls of the levées and from volcanic levels under the lava flows, thus forming a protalus rampart.

The ramp that formed below the frontal moraine during the maximum glacier advances in the L.I.A., entered the floor of Jamapa Pleistocene glacial valley. A glacier from the first Neoglacial advance (3,000–2,000 yr BP) had covered the upper part of the valley (Heine 1975a, 1983, 1988), but its moraines can only be partially traced. The valley has a very clear U-shaped morphology and its floor is covered with recent volcanic material. On the left side, close to the alpine hut (Fig. 2), a lateral moraine morphology is displayed but is now covered by pumitic fall deposits. The pumice extends over all the areas not affected by the erosive processes of the L.I.A.

A series of L.I.A. deposits consisting of a massive main moraine (*ca.* 4300 m) and three to four smaller recessional positions (between 4430 and 4540) was described in Iztaccíhuatl (White1962). They are very similar to those of Pico de Orizaba both in morphology and altitude. The L.I.A. recessional moraines of Iztaccíhuatl were interpreted by Heine (1975a) as a result of short periods of increased precipitation between *ca.* 1850 and 1950.

Recent retreat of Jamapa and other Orizaba glaciers

The glaciers on Pico de Orizaba have steadily retreated during this century (Fig. 4). Heine considers that they reached their maximum L.I.A. advance in 1850. Jamapa Valley moraine of the main



1. L.I.A. maximum advance (Heine 1988; and personal photo-interpretation and fieldwork).
2. The glaciers in 1945 (aerial photo; World Data Center A. at Boulder, CO. USA, and other anonymous photographs).
3. The glaciers in 1958 (Lorenzo 1964).
4. The glaciers in 1971/75 (aerial photo, CETENAL, 11–1971 and 08–1975; and Heine 1975b).
5. The glaciers in 1988 (aerial oblique photo, Zambrano 1988).
6. The glaciers in 1994 (personal observations).
7. Minimum altitude.
8. Year of the data.

Fig. 4. Recent evolution of Pico de Orizaba glaciers (names of glaciers after Lorenzo 1964).

L.I.A. advance is found at 4,395 m and recessional positions at 4,460 and 4,485 m.

The extent of the glacier area in 1945 was determined through the use of a collection of aerial photographs (World Data Center A, Boulder, CO, USA), supplemented with other photos from unknown sources found in different archives and collections. By 1945, the glacier had been reduced to an ice cap whose center lay on the northern side of the new upper cone of Pico de Orizaba. A number of tongues extended from the upper cap, the longest of which is Jamapa Glacier, with a length of 6,000 m from the summit (names of glaciers according to Lorenzo 1964). The end of the tongue was divided into three small tongues separated by the levées of the recent andesitic lava flows described in the foregoing section. The western tongue reached an elevation of 4,590 m and was protected by the wall of Sarcófago Peak. Another tongue located to the east of Jamapa Glacier moved down over the other recent lava flow to an elevation of *ca.* 4,725 m. It is called Chichimeco Glacier. On the eastern side of the cone Oriental Glacier (Eastern Glacier) tongue reached an altitude of 4,900 m and was separated from the ice cap by a narrow corridor. A complex of several glacier tongues on the west side of the cone, was channelled between rocky spurs and even managed to clear steep cliffs. The northwestern tongue, Toro Glacier, descended to nearly 4,600 m. Farther south was a great cascade of séracs that ended at 4,700 m. Two large tongues appeared to the southwest and, despite less favorable aspect conditions, moved down the gentle slope of the recent lavas to 4,900 m.

In 1958 José L. Lorenzo headed a topographic survey of these glaciers (Lorenzo 1964). The changes between 1945 and 1958 are of little significance. Jamapa and Chichimeco tongues had barely receded, although Jamapa was narrower. The glacier which had once covered the youngest lava flows of the north side, only covered its central portion and western edge. Two small tongues at the front were separated by the western levée of the youngest lava flow. The tongue farthest east had advanced to 4,650 m while the western one reached 4,640 m. A space had begun to appear between the western border of the glacier and the wall of Sarcófago Peak, and a debris talus was forming there. Chichimeco Glacier was also becoming narrower and had retreated to 4,750 m. The front of Oriental Glacier had retreated to 5,070 m. The major differences are more apparent on the western glaciers. The cascades had disappeared and the front of the glaciers were located at the edge of great cliffs. The big blocks of ice that piled up at the base were no longer able to regenerate the glacier. Toro Glacier only reached 4,970 m. The southwestern glaciers had retreated (4,980 m) creating a sharp step in the slope in this sector.

The following information is from 1971 and 1975 aerial photographs (CETENAL, XI 71 and VIII 75) and fieldwork conducted during these years by Heine (1975b) (Fig. 4). The observed changes are not very significant, and they probably illustrate the general tendency of other Mexican glaciers to reach a positive balance at the beginning of the 1970's (White 1981). Jamapa Glacier retreated only slightly, and the tongue that was located in the middle of the lava flow extended down to 4,655 m. A much more conspicuous space appeared between the glacier and the wall of Sarcófago peak, where a great debris talus was forming with glacier ice in its interior (Heine 1975b). The Chichimeco tongue was severely reduced, due in part to the gentle slope of the underlying lava. Its front retreated to 4,930 m. A subglacial moraine appeared that was frozen inside (Heine 1975b). Neither Oriental Glacier nor the northwestern glaciers registered significant changes since 1958. The southwestern glaciers, however, had almost completely disappeared.

The next reference is a series of detailed oblique aerial photographs taken in 1988 (Zambrano 1988). Jamapa Glacier had retreated only slightly (4,660 m), while Chichimeco Glacier had disappeared leaving a subglacial moraine. The northwestern and western glaciers had not retreated, but their steep fronts had disappeared. The more than 60 m high cliff formed at the snout had been reduced to a gentle ramp of ice with a front edge that is only 2 to 5 m high. The southwestern glaciers continued to disappear, making it difficult to differentiate between different tongues.

During February 1994, the authors conducted fieldwork at the volcano to determine the extension of Jamapa Glacier with the aid of precision altimeters. Conditions were favorable because there was virtually no snow. According to local climbers, a rocky threshold appeared in 1989 between the ice cap and Jamapa tongue. By 1994 the tongue had been reduced to two patches. The upper edge of the western patch is at 5,013 m (rocky threshold) and splits into two small tongues below the highest visible point of the levée (4,760 m): one tongue is between the levée and the wall of

Sarcófago Peak and reaches a minimum altitude of 4,718 m; the other one, to the east, ends at 4,745 m. The other patch is about 50 meters to the east, between 4,965 m and 4,735 m. Chichimeco Glacier has completely disappeared, so the ice cap on Pico de Orizaba has no tongues on its eastern and northern slopes. The ice cap extends to 5,037 m on the north side. The Oriental Glacier still exists although it is quite small. Its head is still on the edge of the crater but its minimum altitude is 5,100 m. The northwestern glaciers show less differences in their extension. The thickness of ice is probably, at most, a few meters thick and apparently has lost its capacity to flow.

In conclusion, the glaciers of Pico de Orizaba have undergone marked transformations in the last decades. At the beginning of the 20th century, they formed a glacial dome with many tongues that extended in all directions, except to the south. Gradually, the tongues disappeared until the dome was transformed into a simple ice cap with no tongues in the early nineties. Some of these changes were no doubt influenced by critical climatic changes, but topography also controls the pace of the retreating glaciers. For example, a sudden retreat may occur when the glacier moves over a rocky escarpment and cannot regenerate anymore at the base of the latter. This happened to the western glaciers and to the Oriental glacier between 1945 and 1958. The opposite might also explain a sudden retreat. When the slope is gentle the glacier does not retreat much over a given time, but its thickness does diminish. When loss is substantial, the glacier retreats very quickly. This was the case of the southwestern glaciers and Chichimeco Glacier between 1975 and 1988. The same process is operating, but in an earlier phase, on the northwestern and western glaciers, which are apparently moving much slower but still have their tongues.

Jamapa Glacier has retreated very little in the last decades in comparison with the rest. Nevertheless, the thickness of Jamapa Glacier has been greatly reduced. The rocky threshold that now separates the tongue from the ice cap has cut off the lower part of the glacier from its source. The two patches described earlier are now made up of stagnant ice, which will most likely disappear in 5 to10 years.

Geomorphology and geomorphic processes in the recent deglaciated area

The snout of Jamapa Glacier has retreated from 4,590 m in the 1940's to 5,037 m in February 1994, and has left two residual ice patches between these elevations. As a result, approximately 0.5 sq km of glaciated surface is now exposed (Figs 2, 3, 4 and 5).

Almost all this deglaciated surface corresponds to the andesitic lava flows of 1537. The levées of the lava flows show signs of intense glacial abrasion. As a result, the inner sides of the levées are smooth. The ice caused no quarrying effect, and only after it had retreated did a network of decompression fractures appear that destroyed the smoothness and formed sheeting structures that ran parallel to the surface. The outer sides of the levées have vertical slopes, which intersect the base of the lava flow exposing a layer of autobrecciated material. This allowed intense undermining of the edges of the lava flow during and after the peak glacial period. When the ice retreated, gravitational processes set in. At present the edges of the lava flow are covered by a strip of gravity deposits composed of great blocks (between 1 and 5 m in diameter) that fall from the massive part of the lava flow as the base collapses.

Once the ice retreated, the surface of the central part showed a succession of thresholds and basins that largely correspond to original features of the lava flow , modified in detail by the glacier. The thresholds have a small base that measures no more than 30 m in length with a relative height of 15 to 20 m. The summit is sharp and the slopes are steep (60°–75° avg.). The thresholds form a dense labyrinth of pinnacles among small basins. The surface of the thresholds is scarred by abrasion. Sometimes they form roches moutonnées or whalebacks. The numerous fractures on the pinnacles are associated with the decompression process that begins as the ice retreats and forms sheeting structures parallel to the glacial surface. The basins are not filled with till sediment, since is very little of this material available, but there are some large blocks present that have recently fallen from the thresholds. Since the rock is permeable, stream action is very limited.

There is a small basin between the lava flow and the eastern escarpment of Sarcófago Peak (Figs 2 and 3). The escarpment exposes a thick series of alternating lava flows and pyroclastic deposits. A 50 m thick dacitic lava flow appears at the base of the wall and has been severely scoured by glacial abra-

Fig. 5. Jamapa Valley (Pico de Orizaba North Face). The two ice patches into which the old Jamapa glacier is transformed in 1994. On the right, the Sarcófago Wall.

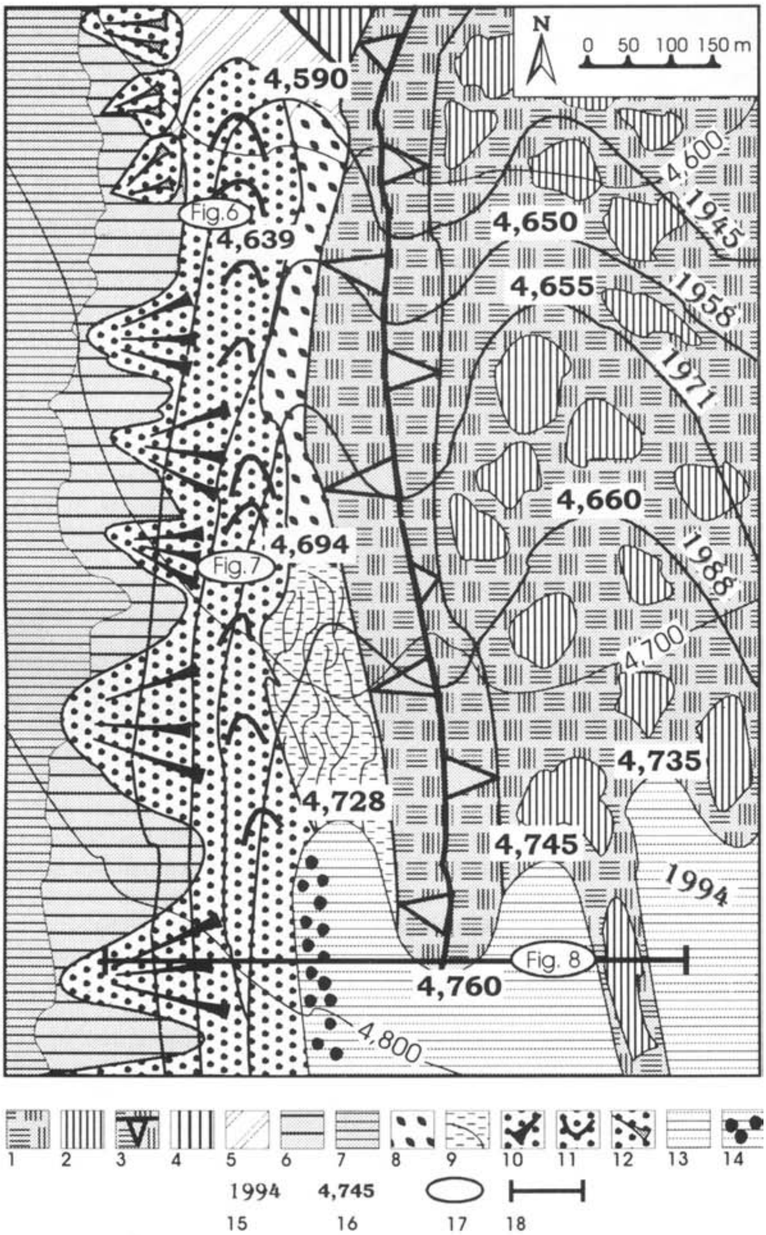
sion. Overlying the lava flow is a 7 m thick ash flow layer which is a weak spot in the wall, often allowing rocks from the upper lava beds to fall.

Frost shattering seems to play an important role in mass movement processes on the wall, although little climatic data is available to confirm this. The weather station on Nevado de Toluca (4,120 m) (see Fig. 1) indicates that there are 220 days of minimum temperatures below 0°C, 183 of which have maximum temperatures above 0°C. The average monthly temperature ranges from 0° to 6°C. Average annual precipitation is 850 mm and most of it occurs in summer (79% of the total falls between May and October) in connection with the trade winds. Precipitation in the form of snow is relatively scarce (13% of the total). It takes place in the summer and also in the winter, when it is associated to the arrival of polar air masses. Hail is the most common type of precipitation (from 21 to 47% of the total) and occurs mainly in summer. (Lorenzo 1969)

Data from the weather station near Paso de Cortés (Cerro Altzomoni, 4,034 m), located between Popocatepetl and Iztaccíhuatl volcanoes, recorded from 1961 to 1968, supplement those from Nevado de Toluca (Lorenzo 1969). There is the same concentration of rainfall in the summer months, but rain rather than hail (17%) is the predominant type of precipitation. This is probably due to the lower elevation. Snow represents only 7% of the precipitation, although this varies greatly depending mainly on winter snowfall. The temperatures also reflect the effects of the 100 m difference in elevation. There are 180 days with minimum temperatures below 0°C.

Studies by Lauer and Klaus (1975) and Lauer (1978) provide significant data on the climatology of Pico de Orizaba (Table 1). Based on long period records from different parts of central Mexico and on direct monitoring in the area of Jamapa Glacier (4,690 m) and two lower points (4,250 and 3,480 m) on the same face, they estimated annual average values of several climatic parameters at 5,000, 4,000 and 3,000 m on the western slope of Pico de Orizaba (Table 1).

Lauer and Klaus (1975) found out that in the



1. Lava flow from 1537.
2. Roche moutonnée on lava ridges.
3. Lava levée.
4. Important scarp.
5. Glacially smoothed surface.
6. Wall with lava layers.
7. Wall with pyroclastic layers.
8. Blockfield.
9. Outwash plain.
10. Talus cone with cover ice.
11. Incipient rock glacier.
12. Rockfall cones without ice.
13. Jamapa glacier in February 1994.
14. Glacier partially covered by rockfall deposits.
15. Year of the glacier extension data.
16. Minimum altitude of the glacier in this year.
17. Location of the data for figures 6 and 7.
18. Cross section Figure 8.

Fig. 6. Geomorphologic features in recent deglaciated Jamapa Area.

area of Jamapa Glacier the changes in temperature affect the rock to a depth of 70 cm. Above 4,000 m temperature passes through freezing point at least 200 days a year, which means that freezing-thawing cycles are potentially frequent.

These data suggest that there are excellent structural and thermal conditions for the development of frost shattering on the rockwalls of Sarcófago peak. Precipitation at this altitude (between 5,000 and 4,600 m) is less than in the lower zones, but most of what is considered normal precipitation falls in the form of hail, with the exception of occa-

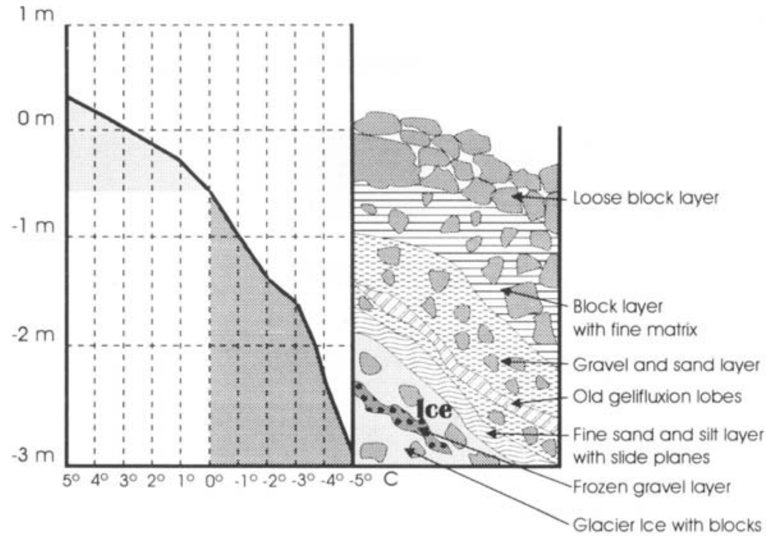


Fig. 7. Jamapa rock glacier fabric and temperatures. Slump ice scarp at 4,639 m of altitude.

sional heavy snowfalls. Thanks to the step-like shape of the wall, snow patches form on the ledges. When they melt, they provide the base of the wall with a year round supply of water. The severely fractured structure of the lava is highly permeable, but water remains stagnant at the contact with less permeable strata of pyroclastic deposits. The snow patches are also a source of frequent snow avalanches that occur after heavy snowfalls and often carry large amounts of debris. These conditions have fostered the rapid development of talus slopes that cover the entire base of the wall and grow as the glacier retreats. They form so fast that when the glacial ice can no longer flow, they trap and incorporate the ice within the deposit.

Fabric and thermal characteristics of talus on the upper Jamapa Valley

The talus is formed by a sequence of coalescent talus cones (Fig. 6). When the glacier moved along the base of the wall, rock and snow slides contributed to the major part of the rock load of the glacier (see section on the L.I.A. moraines above).

Today, it is possible to observe the transition from the most developed talus cones (north), to the incipient talus cones near the glacier (south). The former are situated in the area abandoned by the glacier between 1945 and 1958. Flow oriented in the direction of the valley slope deformed the base of the talus cones evolving into incipient rock glaciers. Sharply pointed concentric ridges of *ca.* 1 m high are a result of these flow structures.

Table 1 Climatic data of Pico de Orizaba (from Lauer and Klaus 1975 and Lauer 1978)

Altitudes in meters	5,000	4,000	3,000	2,500
Mean annual temperature in °C	0	5	10	15
Mean January temperature in °C	-1	3	7	11
Mean July temperature in °C	1	7	13	18
Mean annual temperature variation	-2	-4	-5.5	
Average number of days with minimum temperature below freezing point	360	200	120	50
Average number of days with maximum temperature below freezing point	160	45	0	0
Total precipitacion in mm	800	900	1,200	1,000

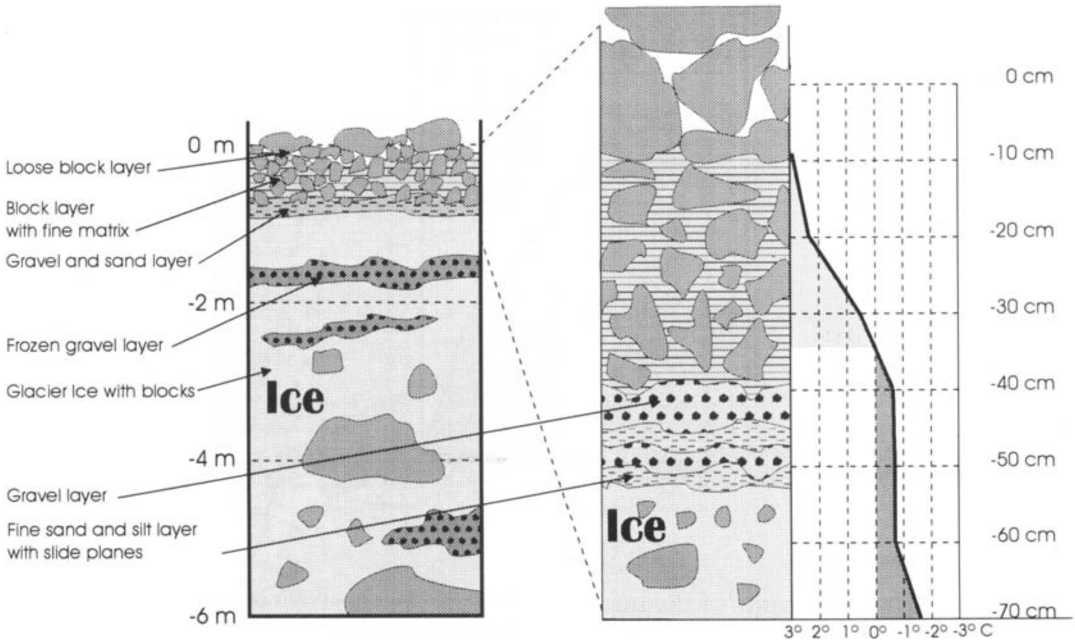


Fig. 8. Jamapa rock glacier fabric and temperatures. Slump ice scarp at 4,694 m of altitude.

At 4,639 m a core sample was taken in one of the talus cones to study its structure and temperature (Fig. 7). Three layers were identified. The upper one had a thickness of 0.5 m and was composed of large and loose blocks (L=1.2 m). The internal temperature of this layer was 0.2°C (in comparison to an air temperature of 18°C). Between 0.5 and 1.6 m, the deposit contains alternating layers of gelifluxion and rockfall material. The layers of gelifluxion contain an abundance of fine matrix and blocks. These blocks are distributed by size, the largest of which have an average diameter of 1.2 m and are at the front of the lobes. The rockfall layers are much more irregular. Their average size is smaller (more than 50% are between 30 and 65 cm in diameter) with little fine matrix. The temperature drops in this layer from 0.2°C to -3°C. Between 1.6 and 1.8 m depth there is a layer of fine sand and silt crosscut by many little slide joints. This seems to mark the place where upper layers slid down over the ice mass. Below 1.8 m, there is blue ice (0.8 density) interspersed with large blocks and gravel layers. The temperature drops more abruptly in the ice, reaching -5.2°C at a depth of 3 m.

Observations were also made on a younger talus cone farther to the south in an area abandoned by the glacier between 1958 and 1988. The layer of rock fragments is much thinner. Ice slumps occur frequently when massive slippage takes place on the buried ice. The resulting scars reveal the inner structure of the deposit. A detailed analysis was made of one of the slump scars found at an altitude of 4,694 m (Fig. 8).

The surface of the deposit is covered with a layer of blocks and loose gravel about 30 cm thick. The temperature drops from 2.4°C at 20 cm to 0.6°C at 30 cm depth. The next layer has approximately the same thickness and consists of a chaotic mix of gravel and sand. The temperature at 60 cm depth is -0.5°C. A third layer is 15 cm thick with alternating layers of fine and coarse sand, crosscut by many slippage planes. Blue ice appears at a depth of 59 cm (density between 0.75 and 0.8) and is intermixed with many blocks and frozen gravel layers. The temperature drops to -2.2°C at 80 cm.

Heine (1975b) studied this area in 1971 and 1975, and stated that the different types of discontinuous permafrost he observed between 4,600 and 5,000 m, including buried glacier ice and soil ice, were fossil features protected by rock debris and associated with the retreat of glaciers since the L.I.A. (Heine 1994). According to Heine, there were two types of discontinuous fossil permafrost:

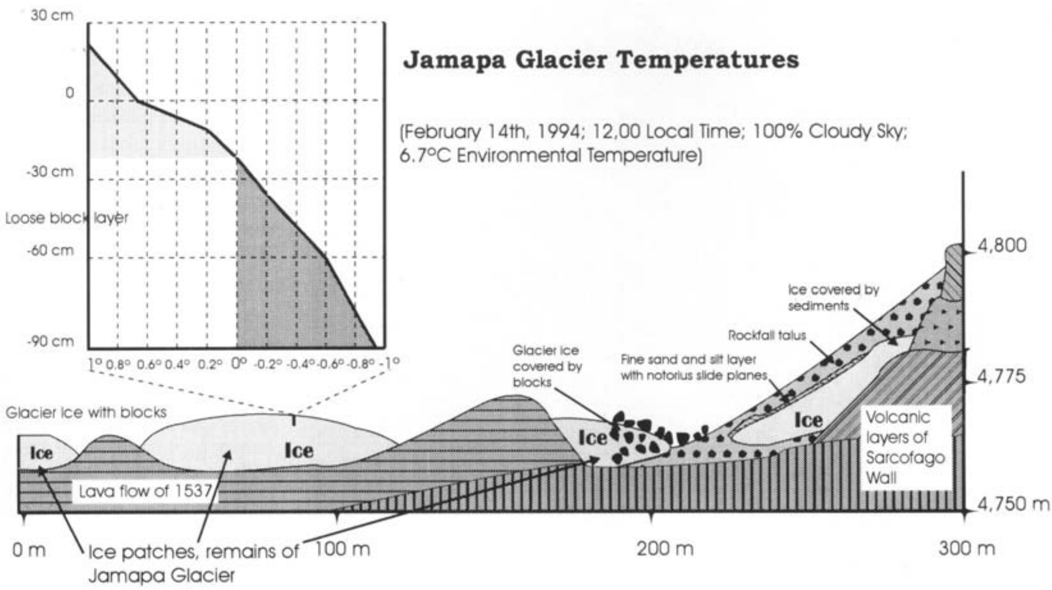


Fig. 9. Cross-section of Jamapa Valley at 4,750 m of altitude and Glacier ice temperatures. See Fig. 6 for location.

(a) glacier ice intermixed with material from lateral moraine; and (b) interstitial ice contained in the moraine. He observed that glacier ice was more than 7 m thick, while interstitial ice exceeded 10 m. The active layer was always thin (10–20 cm in interstitial ice and 60 cm in fossil glacier ice, both equal to the detritial layer that covers it). Heine pointed out that the snowline (5,000 m) is above the lower limit of permafrost (4,600 m), which contradicts the current theory, and proposed three explanations for this: (1) the permafrost in Mexico is a fossil feature; (2) at present the altitude of the snowline in central Mexico (and other dry tropical areas) is determined more by precipitation than by temperature, while in the case of the lower limit of the permafrost the main conditioning factor is temperature; (3) although the mountains of Mexico are in the tropics, they are influenced by non-tropical phenomena such as the polar air masses.

The most recent generation of talus cones is found on the western edge of today's Jamapa Glacier (Figs 9 and 10). As the glacier retreats, the stagnant ice is buried by mass movement deposits. The ice in contact with the wall of Sarcófago Peak, directly below an avalanche path, survives because it is protected by a debris cone. The rest of the glacier continues to disappear. Temperature readings of glacier ice were taken at 4,760 m on one of the remaining patches of the Jamapa glacier. They showed considerably higher temperatures than those of the rock glaciers. The glacier had no snow cover, since there had not been any significant snowfall in the last few weeks. The firn was only 25 cm thick and had a temperature of 0°C (due to insolation). At a depth of 58 cm, the ice had a temperature of -0.6°C. The temperature at 90 cm was -0.9°C.

Conclusions

Jamapa Glacier has been retreating since the beginning of the twentieth century, which is also the case of glaciers in other mountains in Mexico with glaciers (White 1981, Heine 1983). The geomorphic processes that develop as the ice retreats are directly related to the volcanic geomorphology underlying the glacier. The most active processes are found at the base of the eastern wall of Sarcófago Peak, where the structural conditions are prone to mass movement processes and frost shattering: very steep slopes; alternating layers of permeable lava, loose pyroclastic material and impermeable pyroclastic material; formation of

Fig. 10. Slump scar on ice cover debris. Blocks and gravel layers are intercalated in the ice. See hammer for scale. A silt layer, with several slide planes, is covering the ice. On top, a pebble and block layer.

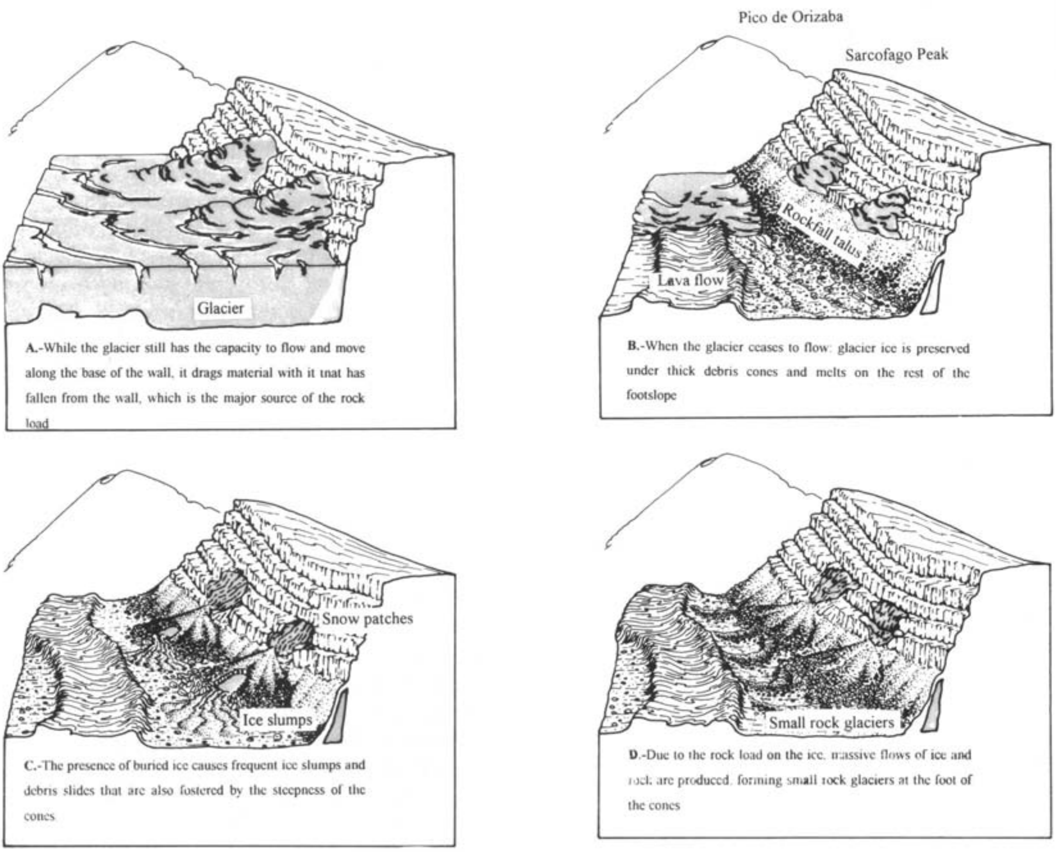


Figure 11. Evolution model of Jamapa Valley.

structural steps where snow accumulates year long and provides a constant source of water to the wall; and frequent snow avalanches that originate from the snow that accumulates on the steps.

The climatic conditions make this wall an ideal place for frost shattering processes. Temperature passes through the freezing point at least 200 days a year. The eastern exposure and the rocky wall make these maximums and minimums even more extreme (Lauer 1978).

The retreat of the glacier creates a sequence in the formation of rock talus (Fig. 11). While the glacier still has the capacity to flow and move along the base of the wall, it drags material with it that has fallen from the wall, which is the major source of the rock load (Fig. 11A). When the glacier can no longer flow or when its front retreats, the ice remains below the fall deposits and first forms a prolonged surface at the bottom of the wall (Fig. 11B). Later, when the glacier ceases to flow, the accumulation of material from the wall glacier ice is preserved under thick debris cones and melts on the rest of the footslope.

The presence of buried ice causes frequent ice slumps and debris slides that are also fostered by the steepness of the cones (Fig. 11C). Due to the rock load on the ice, massive flows of ice and rock are produced, forming small rock glaciers at the foot of the cones (Fig. 11D).

The sequence of processes described occurs only where the sidewalls contribute enough debris to fossilize the motionless ice of the retreating glacier snouts. This explains the fact that the recent retreat of the glaciers has not been followed by the fossilization of glacier ice on most of the slopes of the volcano. The same applies to other mountains of central Mexico (Popocatépetl and Iztaccíhuatl), where the retreat of glaciers has not led to the development of rock glaciers.

The mechanism described here can lead to the formation of small ice-cored rock glaciers. Despite their position at the foot of a talus, these rock glaciers could be erroneously interpreted as ice-cemented rock glaciers (Martin and Whalley 1987) unrelated to glacier ice. Studies of fossil rock glaciers formed from talus on deglaciated valley walls should consider the possible presence of glacier ice as a mechanism of rock glacier formation.

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