# Glaciers of North America–

# GLACIERS OF MÉXICO

*By* SIDNEY E. WHITE

## SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

*Edited by* RICHARD S. WILLIAMS, Jr., *and* JANE G. FERRIGNO

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*Glaciers in México are restricted to its three highest mountains, all stratovolcanoes. Of the two that have been active in historic time, Volcán Pico de Orizaba (Volcán Citlaltépetl) has nine named glaciers, and Popocatépetl has three named glaciers. The one dormant stratovolcano, Iztaccíhuatl, has 12 named glaciers. The total area of the 24 glaciers is 11.44 square kilometers. The glaciers on all three volcanoes have been receding during the 20th century. Since 1993, intermittent explosive and effusive volcanic activity at the summit of Popocatépetl has covered its glaciers with tephra and caused some melting*

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# GLACIERS OF MÉXICO

*By* SIDNEY E. WHITE[1]

## Abstract

Glaciers in México are limited to its three highest mountains, all of which are volcanoes: Volcán Pico de Orizaba (Volcán Citlaltépetl), Volcán Iztaccíhuatl, and the active (since 1993) Volcán Popocatépetl, which have 9, 12, and 3 named glaciers, respectively. The total area of the 24 glaciers is 11.44 square kilometers. All of México's glaciers are small, with areas rarely exceeding a few tenths of a square kilometer, except for the ice cap and firn field of Gran Glaciar Norte on Citlaltépetl, which has an area of 9.08 square kilometers and from which seven outlet glaciers emanate. The small areal dimensions of México's glaciers severely restrict the usefulness of Landsat multispectral scanner images for delineating individual glaciers or for monitoring variations in terminus position. The nearly threefold improvement in spatial resolution of the Landsat 3 return beam vidicon images compared to multispectral scanner images (30-meter versus a 79-meter pixel), permits a more accurate delineation of the mountain glaciers of México.

## Introduction

Under the present climatic conditions, three volcanoes in south-central México, all having highest elevations in excess of 5,000 m, support numerous small glaciers. (1) Volcán Pico de Orizaba (Volcán Citlaltépetl)[2], a 5,610-m-high (Simkin and Siebert, 1994; previous value was 5,675 m) stratovolcano in the State of Veracruz, supports nine named glaciers. Seven volcanic eruptions have been recorded there in historic time, the last in 1687 (Simkin and others, 1981). (2) Volcán Iztaccíhuatl, a 5,230-m-high (Simkin and Siebert, 1994; previous value was 5,286 m), dormant Holocene stratovolcano in the State of Puebla, has three summits and 12 named glaciers. (3) Volcán Popocatépetl, a 5,465-m-high (Simkin and Siebert, 1994; previous value was 5,452 m) stratovolcano in the State of Puebla, has three named glaciers. Since 1345, Popocatépetl has been the site of at least 25, and perhaps as many as 30, eruptions, the last at this writing in January 2001 (Simkin and Siebert, 1994; Smithsonian Institution, 1994, 1995, 1996, 1997, 1998, 1999, 2000; Roberto Quaas, written commun., 1997). The author also observed one gas-column eruption on 7 April 1953.

The equilibrium line altitude (ELA) of glaciers on Iztaccíhuatl and Popocatépetl is 4,880 m and 4,925 m, respectively; the ELA of glaciers on Citlaltépetl is not known. No other highland areas in México are sufficiently high to be above the present-day snowline. During the Illinoian age of the Pleistocene Epoch, however, the ELA was as low as 3,510 m on Iztaccíhuatl during the Tonicoxco (*Tomicoxco*) advance and was somewhat higher

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[1] Department of Geological Sciences, Ohio State University, 275 Mendenhall Laboratory, 125 South Oval Mall, Columbus, Ohio 43210–1398.

[2] Most of the geographic place-names used in this section are from the Gazetteer of Mexico (U.S. Board on Geographic Names, 1992). An exception is Citlaltépetl, where the Nahuatl place-name is used instead of the Spanish one (Volcán Pico de Orizaba). Throughout the text, references to Citlaltépetl, Iztaccíhuatl, and Popocatépetl are, after the first mention, without Volcán in the title. A few names not listed in the gazetteer are shown in italics.

during other advances. Cerro Ajusco, a 3,937 m-high volcanic mountain south of Mexico City in the Federal District (D.F., Distrito Federal), supported glaciers during times of lower ELA during the late Wisconsinan age and during the late Holocene Epoch (early neoglaciation and middle neoglaciation) (White, 1981a, 1984). The following discussion of the glaciers on Citlaltépetl, Iztaccíhuatl, and Popocatépetl emphasizes historic and modern observations.

## Volcán Pico de Orizaba (Volcán Citlaltépetl)

At 5,610 m (Simkin and Siebert, 1994; previous value was 5,675 m, which is used as the reference elevation in the text for glacier elevations), Citlaltepétl is the highest mountain in México and the third highest on the North American Continent. It contains the largest ice cap and firn field in México (Gran Glaciar Norte) and has nine named glaciers (fig. 1 and table 1), including the ice cap, its seven outlet glaciers, and a mountain (niche) glacier. Its name is derived from the Nahuatl words Citlalli (star) and tépetl (mountain). However, its officially recognized name is Spanish, Pico de Orizaba. Situated at lat 19°02' N. and long 97°17' W., it is 210 km east of Mexico City and 120 km west of Veracruz and the Gulf of Mexico. Topographic maps of Citlaltépetl are sold by the Comisión Cartográfica Militar, Secretaría de la Defensa Nacional, México, D.F. Provisional maps by Estudios y Proyectos, Asociación Civil (A.C.), México, D.F., also may be purchased. Vertical aerial photos taken in 1955 by the Comisión del Papaloapan are in the Instituto de Geografía, Universidad de México, México, D.F. Oblique aerial photographs taken in 1942 are available from Compañía Mexicana Aerofoto, Sociedad Anónima (S.A.), México, D.F.

Because of its inaccessibility due to the 210-km distance from Mexico City and the 42-km journey from *Tlalchíchuca* or the 46-km trip from *San Andres Chalchícomula* by alternate third-class roads to trailheads from the northwest (fig. 2), Citlaltépetl rarely has been studied from any viewpoint. However, being the highest and the most esthetic mountain in México—a white shining star in the east—it caught the attention of Europeans early in the development of the country and was climbed several times from the mid-1800's to the early 1900's (Galeotti, 1850; Plowes and others, 1877; Angermann, 1904; Waitz, 1910). Glaciers and snowfields were mentioned in the description of these climbs because they were along the logical routes of ascent; unfortunately, scientific details are scarce in these works.

TABLE 1.—*Nine named glaciers of Citlaltépetl*

[Taken from Lorenzo, 1964, sketch III. Leaders (--), not known]

| Glacier number | Glacier name | Glacier type | Area (square kilometers) |
|---|---|---|---|
| | Gran Glaciar Norte | Ice cap, firn field | 9.08 |
| I | Lengua del Chichimeco | Outlet | -- |
| II | Glaciar de Jamapa | Outlet | -- |
| III | Glaciar del Toro | Outlet | -- |
| IV | Glaciar de la Barba | Outlet | -- |
| V | Glaciar Noroccidental | Outlet | -- |
| VI | Glaciar Occidental | Outlet | -- |
| VII | Glaciar Suroccidental | Outlet | -- |
| VIII | Glaciar Oriental | Mountain (niche) | .42 |
| | | Total | 9.50 |

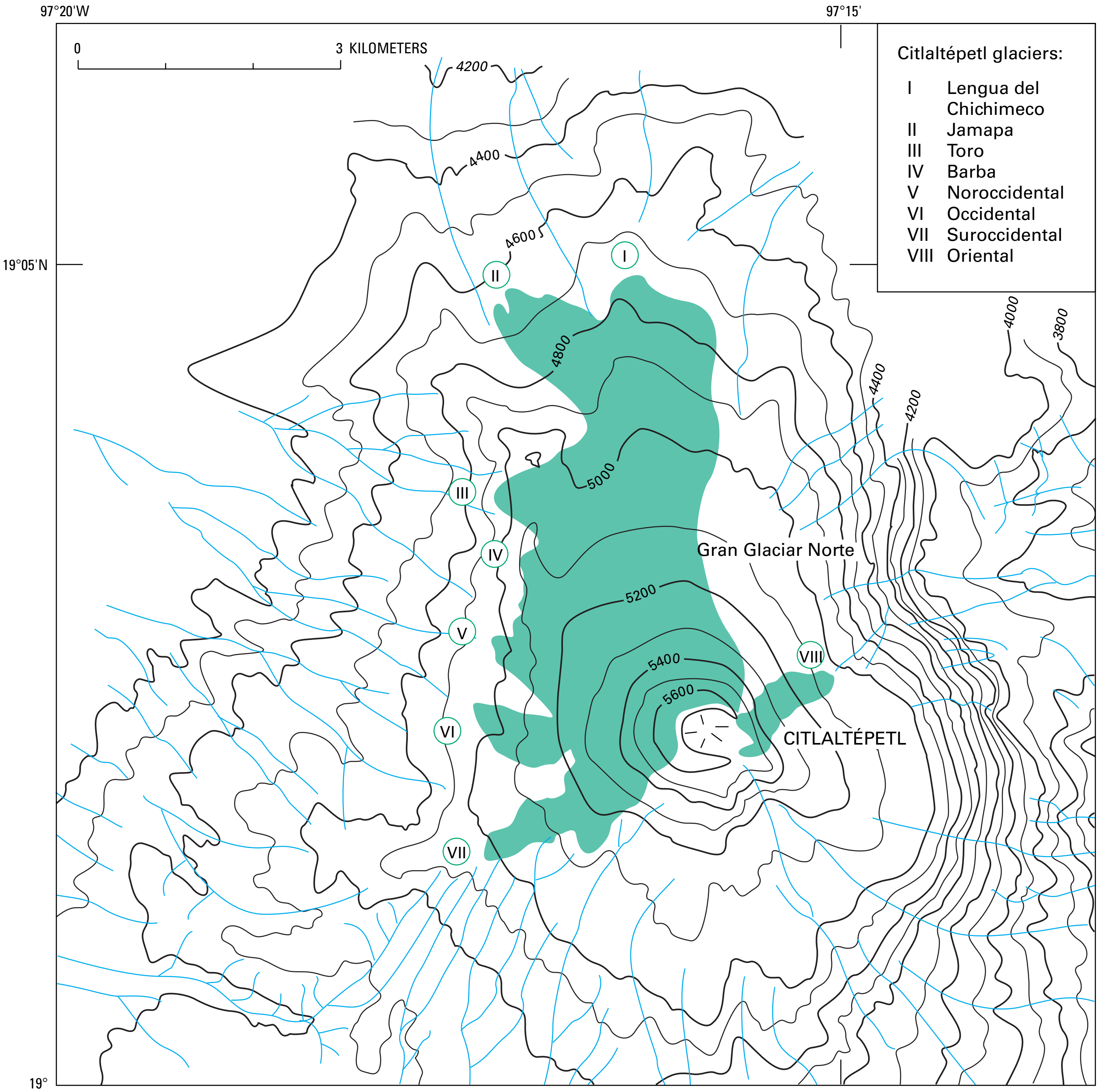



***Figure 1.**—Glaciers (shown in green) on Citlaltépetl. The numbers refer to the named outlet and mountain glaciers listed in table 1. Contour interval, 100 m. Original map by Estudios y Proyectos, A.C., México, D.F. (Modified from Lorenzo, 1964, sketch III.)*

Blásquez (1957) may have been the first to study Citlaltépetl's glaciers from a glaciological viewpoint. He studied from a hydrogeological perspective the meltwater that is used locally. The most exacting study of Citlaltépetl's glaciers was by a team of mountaineering geophysicists led by José Luis Lorenzo in 1958, working under the auspices of the Comité Nacional de México for the International Geophysical Year (1957–58) through the Instituto de Geofísica. Despite hardships of elevation and unforeseen storms, the team measured glacier-surface slopes, accumulation areas, and elevations of glacier termini. In addition, they carried out topographic mapping of the nine glaciers and took scores of excellent photographs (Lorenzo, 1959, 1964). The retreat of the northernmost outlet glacier, Glaciar de Jamapa, is recorded by Palacios and Vázquez Selem (1996). No other scientific work on Citlaltépetl glaciers is known, except for an occasional mention in mountaineering journals.

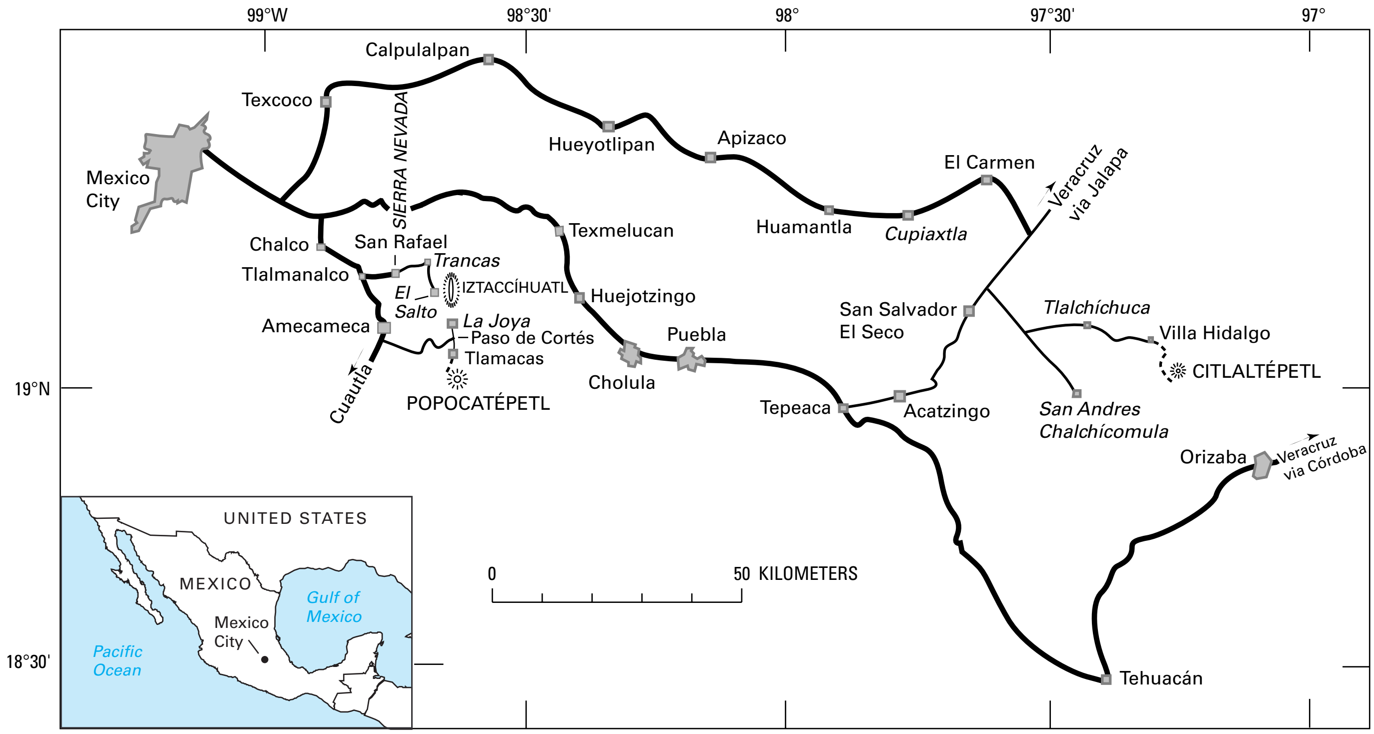



*Figure 2.*—*Principal overland routes to Citlaltépetl, Iztaccíhuatl, and Popocatépetl. Paved roads are shown in broadest lines; trails, in dashed lines. (Modified from Lorenzo, 1959, sketch II.)*

A temperate, humid climate with periodic rainy seasons, although drier in winter, surrounds Citlaltépetl up to about 4,300 m. Above this, tundra and ice-cap climates prevail to the summit. Heavy snowfall probably occurs both in winter and summer, as it does on the other high volcanoes. Snow falling on the south and southeast sides melts quickly because of solar radiation but persists on the northwest and north sides. Aided by the insolation angle and wind redeposition, the persistent snow cover develops into a huge accumulation area and firn field, which serves as a source for the outlet glaciers.

The entire north side of the upper Citlaltépetl cone is covered by the Gran Glaciar Norte of Lorenzo (1959), which fills an elongate highland basin with near-radial flow and is the source area for seven outlet glaciers (figs. 1 and 3). The main glacier extends 3.5 km north of the crater rim, has a surface area of about 9.08 km$^2$, and descends from 5,650 m to a little below 5,000 m (Lorenzo, 1964, fig. 12). It has a slightly irregular and stepped profile that is caused in part by the configuration of the bedrock. Most crevasses show an ice thickness of approximately 50 m.

Below the 5,000-m elevation on the north side of the volcano, the outlet glaciers Lengua del Chichimeco and Glaciar de Jamapa extend north and northwest another 1.5 km and 2 km, respectively. The terminal lobe of Lengua del Chichimeco at 4,740 m, having a gradient of only 140 m km$^{-1}$, is a low, broad ice fan that has a convex-upward profile (Lorenzo, 1964, fig. 10), a front typical of almost all Mexican glaciers. The most distinct glacier is Glaciar de Jamapa, which leaves Gran Glaciar Norte (figs. 1 and 3) at about 4,975 m and, after 2 km with a gradient of 145 m km$^{-1}$, divides into two small tongues that end at 4,650 m and 4,640 m. Both tongues terminate in broad convex-upward ice fans thinning along their edges (Lorenzo, 1964, figs. 14 and 15). The retreat of these tongues prior to 1994 produced much erosion downstream and buried their edges by ablation rock debris (Palacios and Vázquez Selem, 1996).

The west side of Gran Glaciar Norte generates five outlet glaciers (fig. 1). From north to south, the first two, Glaciar del Toro and Glaciar de la Barba (fig. 3), are hanging cliff or icefall glaciers, reaching the tops of giant lava steps (Lorenzo, 1964, fig. 18) at 4,930 m and 5,090 m, respectively. They then descend 200 to 300 m farther down into the heads of stream valleys as huge ice blocks but are not regenerated there. One kilometer farther south, Glaciar Noroccidental (fig. 3), a small outlet glacier 300 m long (Lorenzo, 1964, figs. 21 and 22), drains away from the side of Gran Glaciar Norte at about 5,100 m and draws down the ice surface a few tens of meters over a distance of 500 m, descending to 4,920 m with a gradient of 255 m $km^{-1}$. One kilometer still farther south, Glaciar Occidental (fig. 3) breaks away from Gran Glaciar Norte west of the summit crater at about 5,175 m as a steep, 1-km-long glacier (Lorenzo, 1964, figs. 22 and 23) having a gradient of 270 m $km^{-1}$ that ends at 4,930 m. From the southwest corner of the mountain, another outlet glacier, Glaciar Suroccidental, 1.6 km long, flows from Gran Glaciar Norte at 5,250 m (Lorenzo, 1964, figs. 22 and 23) with a gradient of 200 m $km^{-1}$, which also ends at 4,930 m in a long smooth surface.

East of the summit cone, a separate steep niche glacier, Glaciar Oriental, 1.2 km long and having a gradient of 440 m $km^{-1}$ (fig. 1), flows down the mountainside from about 5,600 m to 5,070 m; it contains many crevasses and seracs (Lorenzo, 1964, figs. 24 and 25) and is the most difficult glacier to climb.

Lorenzo (1964) calculated that Glacier Oriental had a surface area of about 420,000 $m^2$ in 1958, which makes the total area of glaciers and firn field on Citlaltépetl about 9.5 $km^2$. No earlier historical record of glacier tongue activity (advance or recession) is known for Citlaltépetl's glaciers.

Figure 4 is a Landsat 1 multispectral scanner (MSS) false-color composite image of Citlaltépetl and environs on 25 May 1973. Although the Gran Glaciar Norte ice cap is covered with snow, it is possible to see the seven outlet glaciers on the irregular west margin of the ice cap, especially Glaciar de Jamapa and Glaciar Occidental. The 79-m picture element (pixel) of the MSS image makes it difficult to delineate the termini of the seven outlet glaciers from the ice cap. Glacier Oriental, the niche glacier on the east, is not discernible in figure 4.


***Figure 3.****—Citlaltépetl from the northwest. Gran Glaciar Norte is the high, white cone in the center. Glaciar de Jamapa, one of the seven outlet glaciers from Gran Glaciar Norte, is on the left skyline. The outlet glaciers Glaciar del Toro and Glaciar de la Barba are visible in the center; the outlet glaciers Glaciar Noroccidental and Glaciar Occidental are in the upper right. Oblique aerial photograph taken in February 1942, courtesy of Compañía Mexicana Aerofoto.*

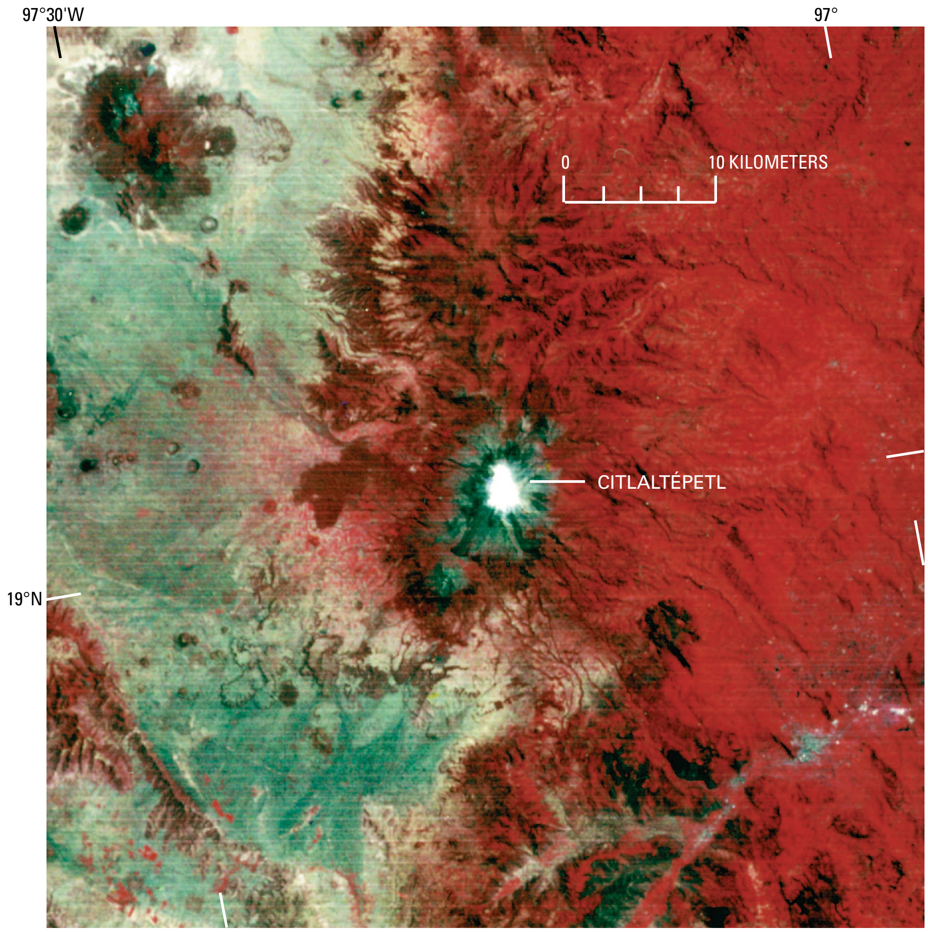



***Figure 4.****—Enlargement of part of a Landsat 1 MSS false-color composite image (1306–16231; 25 May 1973; Path 26, Row 47) of Citlaltépetl and environs. Landsat image from the EROS Data Center, Sioux Falls, S. Dak.*

TABLE 2.—*Twelve named glaciers of Iztaccíhuatl*

[Taken from Lorenzo, 1964, sketch VII]

| Glacier number | Glacier name | Glacier type | Area (square kilometers) |
|---|---|---|---|
| I............ | Glaciar de la Cabeza | Mountain, ice cap | 0.014 |
| II .......... | Glaciar del Cuello | Mountain, valley | 0.050 |
| III ......... | Glaciar de Ayolotepito | Mountain, cirque, valley | 0.213 |
| IV ......... | Glacier Norte | Mountain, niche, hanging, interrupted | 0.046 |
| V........... | Glaciar del Cráter | Mountain, crater, interrupted, cascading | 0.180 |
| VI ......... | Glaciar Oestenoroeste | Mountain, ice cap, hanging | 0.050 |
| VII ........ | Glaciar Nororiental | Mountain, firn field,valley | 0.025 |
| VIII....... | Glaciar Centro Oriental | Mountain, firn field, valley | 0.245 |
| IX ......... | Glaciar de Ayoloco | Mountain, cirque, valley | 0.247 |
| X .......... | Glaciar Sudoriental | Mountain, firn field | 0.078 |
| XI ......... | Glaciar Atzintli | Mountain, ice apron | 0.058 |
| XII........ | Glaciar de San Agustín | Mountain, niche | 0.011 |
| | | Total | 1.217 |

## Volcán Iztaccíhuatl

At 5,230 m (Simkin and Siebert, 1994; previous value was 5,286 m, which is still authoritative and is used as the reference elevation in the text for glacier elevations), Iztaccíhuatl is the third highest peak in México and the seventh highest on the continent. It has 2 firn fields and 12 named glaciers (fig. 5 and table 2). Its name is derived from the Nahuatl words Iztac (white) and cíhuatl (woman). When viewed from the west (fig. 6), the long profile from north to south conjures up the head, neck, chest, stomach, knees, and feet of a recumbent sleeping woman covered with a white shroud. Its name, often misspelled, is incorrectly translated in places. The highest of three summits, *El Pecho*, is situated at lat 19°10'30" N. and long 98°38'30" W. The 12 named glaciers are scattered along a north-south distance of approximately 3 km. Iztaccíhuatl can be seen from Mexico City, lying only 64 km to the southeast

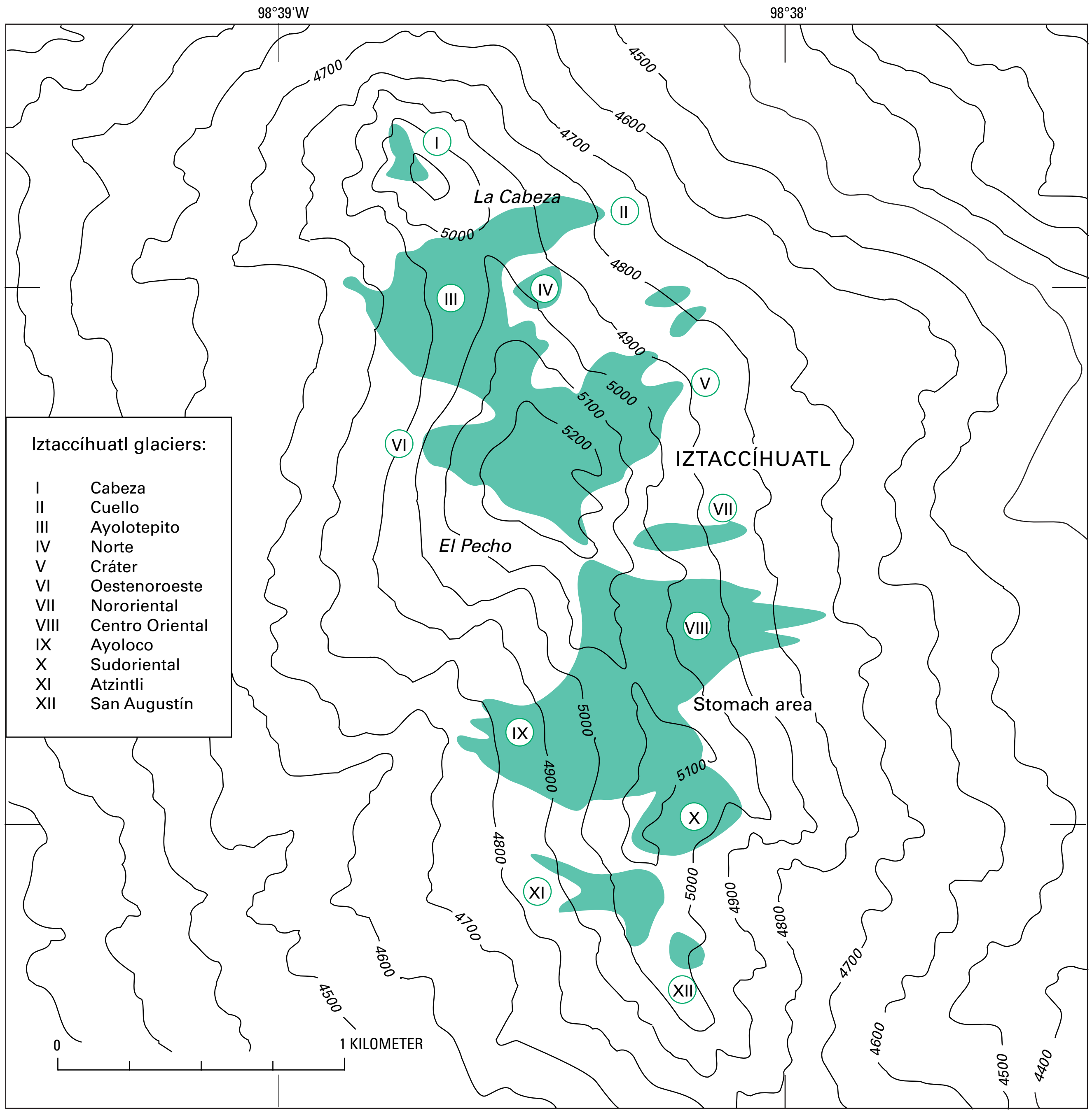



***Figure 5.**—Glaciers on Iztaccíhuatl. The numbers refer to the named glaciers listed in table 2. Contour interval, 100 m. (Modified from Lorenzo, 1964, sketch VII.)*

**Figure 6.**—*Iztaccíhuatl from the west. At the far left of the photograph, partly under clouds, is the separate, irregularly eroded Volcán Teyotl. Next is the higher, snow-covered, cliff-encircled peak, La Cabeza, with Glaciar de la Cabeza sloping to the left. The highest ice-covered peak is El Pecho (5,286 m), with the firn field in the "neck" between it and La Cabeza, source of Glaciar de Ayolotepito. The ice-covered peak of El Pecho is Glaciar Oestenoroeste. South of El Pecho (right) is the "stomach area" firn field, source of Glaciar de Ayoloco. Glaciar Atzintli is to the right of the "stomach area," but in the photograph, a recent snowfall joins all into one snowfield. La Joya (fig. 2) is at the right side of the photograph. Oblique aerial photograph taken in February 1942, courtesy of Compañía Mexicana Aerofoto.*

near the southern end of the *Sierra Nevada* (fig. 2). Only one topographic map is needed, Iztaccíhuatl 14Q–h(107), which is sold by the Secretaría de la Defensa Nacional. Vertical aerial photos that have excellent quality and flight-line precision and were taken in 1945 by the Compañía Mexicana Aerofoto are easily purchased; these photographs were used by the company for the preparation of the maps by photogrammetric techniques. Oblique aerial photographs taken in 1942 and more recently are also available from Compañía Mexicana Aerofoto.

The proximity of Iztaccíhuatl to Mexico City and the relative ease in reaching the mountain from both the east and the west enticed many scientists and mountaineers to climb it and to observe the glaciers. Although not recommended, from the east side one may leave the old Mexico City—Puebla Highway at Texmelucan or at Huejotzingo (fig. 2) and drive 5 to 10 km onto the broad east slopes of the range. The field party should be accompanied by Spanish-speaking persons in order to explain its presence in the area. From Mexico City, however, a paved highway via Chalco and Tlalmanalco past the paper factory at San Rafael (fig. 2), a distance of about 50 km, allows access onto the northwestern and western slopes of the mountain by means of mountain roads and four-wheel-drive vehicles. From San Rafael, it is 7 km up to *Trancas* and 6 km more to the end of the road at *El Salto* at 3,750 m. From *El Salto*, the glaciers at 4,770 m and a mountain refuge are only 3 km distant. The route used most by climbers from Mexico City is about 65 km by Chalco and Amecameca up a paved mountain road to Paso de Cortés at 3,680 m, and then north on a poor road 3.5 km to its end at the south end of the mountain at *La Joya*, which is 4,000 m high (fig. 2). From here, the peaks above the glaciers and mountain refuges are reached in 3.5 km by a climber's route above 4,500 m along the crest of high peaks.

The oldest reference to glaciers on Iztaccíhuatl was made by José Antonio de Alzate y Ramírez sometime between 1781 and 1789 (Alzate y Ramírez, 1831; cited in Lorenzo, 1964). Not until 1890 did other reports on the glacier ice appear (Whitehouse, 1890; Heilprin, 1890, who briefly mentioned glaciers on Iztaccíhuatl, including a crevassed one he named the "Porfirio Diaz Glacier," probably Glaciar de Ayoloco). Several scientists discussed cirques on the west side, the glaciers in them, and meteorological factors responsible (Ordóñez, 1894; Farrington, 1897; Böse and Ordóñez, 1901; Brecker, 1908; Melgarejo, 1910; Freudenberg, 1911). The hydroelectric possibilities of glacier meltwater were studied by Paredes (1922), and glaciers and their climatic situation, by Jaeger (1925, 1926) and Prister (1927). Robles Ramos (1944) conducted hydrologic and meteorologic studies in 1942 on the west side and related glacier melting to streamflow. De Terra (1947), De Terra and others (1949), White (1962, 1981a), and Vázquez-Selem and Phillips (1998), discussed the glaciers in relation to former glaciations.

According to Vázquez-Selem and Phillips (1998), the glacial deposits on Iztaccíhuatl volcano provide the "most complete record of [past] glaciation of central México." Their glacial chronology is based on dating moraines with the $^{36}Cl$ cosmogenic isotope and tephra from Popocatépetl. The Nexcoalango moraines at 3,100 m described by White (1962) are dated at between 151 and 126 Ka [marine isotope stage (MIS) 6]; the Hueyatlaco Moraines of White (1962), associated with the last global glacier maximum (LGGM), are dated at 20 to 14 Ka. A major deglaciation of Iztaccíhuatl started at 14–13 Ka; Little Ice Age (LIA) moraines are located at 4,300 to 4,700 m.

The elevations of 3 glacier termini in 1953 and 1955 appeared in White (1956), and the elevations of all 12 glaciers in 1959–60, in Lorenzo (1964). The best account by far of Iztaccíhuatl glaciers is that by Lorenzo and his colleagues.

A temperate-rainy climate with no conspicuous dry season encircles the lower slopes of the *Sierra Nevada* and the upper flanks of Iztaccíhuatl to about 4,000 m. Although rain falls every month, summer is the wettest and winter is the driest time of year. Snow falls as low as 4,000 m from November through January. Above 4,000 m are tundra and ice-cap climates. Snow accumulates on all slopes above 4,500 m not only in winter but also from June through middle-August. The volume of precipitation apparently decreases markedly above 4,000 m, but no record of rainfall and snowfall is known for the upper mountain slopes. The 5.8-km-long north-south axis of Iztaccíhuatl plus the location, orientation, and elevation of the highest peaks affect local wind directions during snowfall and provide protection from insolation. On the basis of all these factors, accumulation areas of firn develop above 5,000 m and serve as the source area for 8 of the 12 glaciers. Vázquez Selem (1989), however, in his study of periglacial features, discovered ice cores covered with detritus in the rock glaciers at about 4,400 m on the north side of the peak of Volcán Teyotl (fig. 6), a lower, much-eroded volcano north of Iztaccíhuatl. Small firn fields and ice glaciers existed there during the most recent neoglaciation, but they are now melted.

Most Iztaccíhuatl glaciers originate above the 5,000-m elevation in simple basins and become short, cascading mountain glaciers. Two on the west side, Glaciar de Ayolotepito and Glaciar de Ayoloco (fig. 6), are thickest in cirquelike valley heads. They are neoglacial remnants and have huge early neoglacial moraines and four small inner moraines in front of the ice (White, 1956), probably all built within the last 3,000 years. Three glaciers start from a high transection firn field that has flow both to the east and west (Glacier del Cuello, Glaciar de Ayolotepito, and Glaciar Norte), and two start from *El Pecho* (Glaciar del Cráter and Glaciar Oestenoroeste). Glaciar del Cráter on *El Pecho* occupies a now-dormant crater, although it was active as recently as post-early neoglaciation, possibly between 3,000 and 2,500 years ago. Because the early neoglacial moraines are covered with volcanic scoria from the now-dormant crater, scoria that has been verified petrographically, this suggests that the volcano should be considered to be dormant rather than extinct. The descriptions and measurements of Iztaccíhuatl glaciers that follow are from Lorenzo (1964), plus information added from White (1956) and White's unpublished fieldwork.

Glaciar de la Cabeza is a thin lens of ice of 14,400 $m^2$ on the northwest summit of *La Cabeza* and extends only 200 m northwest from about 5,145 m to slightly lower than 5,000 m (figs. 5 and 6; Lorenzo, 1964, fig. 48). It stops above cliffs, but during neoglaciation, it regenerated at the cliff bottom and built moraines north of *La Cabeza*.

Glacier del Cuello flows east from the transection firn field occupying the "neck" (Cuello). Beginning at 4,990 m, it extends 550 m to 4,760 m on a gradient of 420 m $km^{-1}$ (Lorenzo, 1964, fig. 49), covers about 50,000 $m^2$, and enters a valley on the northeast side of Iztaccíhuatl. Glaciar de Ayolotepito originates from the same firn field, also at 4,990 m, and, in part, from a firn field on the north side of *El Pecho* at 5,250 m (figs. 5 and 6). It turns to the west 900 m from the summit area down into the cirquelike Ayolotepito valley head, where it has a gradient of 520 m $km^{-1}$. In 1959–60 it terminated at 4,760 m (Lorenzo, 1964, figs. 40 and 50) and occupied 212,500 $m^2$, but in 1953, it ended at about 4,670 m (White, 1956). Thus, it had retreated 90 m in elevation and about 125 m in distance in the 6 to 7 years, or about 19 m $a^{-1}$. If the accuracy of a barometer used by Böse and Ordóñez (1901) in November 1898 is reliable, then the terminus of Glaciar de Ayolotepito at 4,610 m had receded only 150 m in elevation or about 460 m distance in the 61 to 62 years since they visited the mountain. This is a rate of retreat of about 7 m $a^{-1}$, much slower than the retreat between 1953 and 1959–60. The third glacier developed from the Cuello firn field and north side of *El Pecho* is Glaciar Norte. It is a small hanging glacier totaling 46,200 $m^2$ that flows northeast from *El Pecho* at 5,250 m, down to cliff tops at 5,050 m, where it is interrupted. It regenerates below the cliffs at 5,010 m and, as a broad tongue, runs down to 4,910 m (Lorenzo, 1964, figs. 43, 51, 52).

Glaciar del Cráter starts on *El Pecho* at 5,286 m and cascades as a cliff glacier northeast, breaking into chaotic icefalls on a gradient of 755 m $km^{-1}$ to 4,965 m, where it bifurcates into two lobes (Lorenzo, 1964, figs. 52 and 53). The longer northeast tongue continues to 4,890 m, where it is interrupted by cliffs and regenerates below in isolated masses extending to 4,750 m and 4,770 m. The shorter east tongue of accumulated ice blocks and great seracs ends above cliffs at 4,910 m. The whole Glaciar del Cráter covers about 179,500 $m^2$. On the northwest side of *El Pecho*, another cliff glacier, Glaciar Oestenoroeste (fig. 6), also descends from the mountaintop at 5,286 m to 5,010 m on a gradient of 835 m $km^{-1}$ and covers about 50,000 $m^2$ (Lorenzo, 1964, fig. 54). The subdivision of this glacier system north of *El Pecho*, including the Cuello firn field and up to the top of *El Pecho*, is based on ice-surface topography and not on direction of ice movement. Southeast of *El Pecho* and separate from any other ice body is a small 400-m-long firn field of 25,000 $m^2$ sloping east from 5,060 m to 4,830 m, named Glaciar Nororiental (Lorenzo, 1964, fig 55).

A second high-transection firn field that produces a glacier system lies 0.5 to 1 km south of *El Pecho* above 5,000 m in the stomach area of Iztaccíhuatl (fig. 5). Glaciar Centro Oriental, which flows to the east, has as its source about 45,000 $m^2$ of firn on the ridge southeast of *El Pecho*. It drops from 5,190 m to 4,850 m, with a gradient of 550 m $km^{-1}$ and is about 0.5 km wide and long. Its terminus divides into three lobes; the longest and lowest lobe ends at 4,715 m. The whole glacier covers about 245,000 $m^2$ (Lorenzo, 1964, fig. 56).

On the west side of the same ridge, and including about 50,000 $m^2$ of firn as its source, is the largest and best known glacier in México, Glaciar de Ayoloco, occupying in 1959–60 about 247,000 $m^2$. In almost all early reports of glacier ice on Iztaccíhuatl, it was Glaciar de Ayoloco that was observed (fig. 6). In 1959–60 it was approximately 0.5 km wide at its head between two high rock buttresses, *Peña Ordóñez* and *Peña Aguilera*, and had seracs, crevasses about 50 m deep, and an irregular bumpy surface (Lorenzo, 1964, fig. 57). Glaciar de Ayoloco descends a distance of 625 m from 5,190 m to 4,725 m on a gradient of 745 m $km^{-1}$. In 1955, the glacier ended at 4,668 m (White, 1956, table 1) and thus, to reach Lorenzo's 1959–60 position, had retreated 57 m in elevation and about 100 m in distance in the intervening 4 to 5 years, an average rate of about 22 m $a^{-1}$. However, comparison of the position of Glaciar de Ayoloco in a photograph taken 1 November 1898 (Böse and Ordóñez, 1901, fig. 2) with photographs taken at the same site by Lorenzo shows the terminus at White's 4,465-m (third) inner stadial moraine. This gives a retreat of about 260 m in elevation, about 810 m in distance, and an average rate of retreat about 13 m $a^{-1}$ in the 61 to 62 years. A photograph in Melgarejo (1910, no. 8), presumably taken in the summer of 1910, shows the terminus of Glaciar de Ayoloco about at White's 4,540-m (fourth) inner stadial moraine (White, 1956, table 1). Vertical aerial photographs taken in November 1945 reveal a thin ice tongue at about 4,560 m, perhaps no longer active due to its tenuity in a protected position below a high rock ridge on the Ayoloco valley-head bottom, about 260 m downvalley from its 1955 position. On the other hand, Böse and Ordóñez (1901) obtained a November 1898 barometric elevation for Glaciar de Ayoloco of 4,545 m. If this elevation is accurate, then in 61 to 62 years, the glacier receded 180 m in elevation and about 475 m in distance compared to Lorenzo's position, or at an average rate of about 8 m $a^{-1}$. This is a much slower rate than that between 1955 and 1959–60, although it is quite consistent with the average rate of retreat of the Glaciar de Ayolotepito during the same period. From all these historic fluctuations, however disparate, it is evident that Glaciar de Ayoloco has been continuously retreating since the 1890's.

A third glacier also of this stomach-area system is Glaciar Sudoriental which has an area of about 77,500 $m^2$. It is moving toward the southeast, is only about 270 m long, and descends from about 5,110 m to 4,990 m (Lorenzo, 1964, fig. 58) on a gradient of 445 m $km^{-1}$.

Based on photographic documentation, Glaciar de Ayoloco and the next glacier 200 m to the south, prior to 1918, had been all one glacier, but in 1953, White realized that a name was needed for this small, separate, thin ice mass. Following the suggestion of José Luis Lorenzo, it was named Atzintli Glacier (White, 1956, p. 294). Glaciar Atzintli, now isolated south of the stomach area (figs. 5 and 6), was only 460 m long in 1959–60, starting at 5,085 m and ending at 4,855 m. It had an area of 57,500 $m^2$ (Lorenzo, 1964, figs. 40, 41, 59) and a gradient of 500 m $km^{-1}$. In 1953, its terminus had been at 4,785 m (White, 1956, table 1), which indicates a recession of 70 m in elevation over a 140 m distance, or about 21 m $a^{-1}$ in the 6 to 7 years, similar to the retreat rate of 22 m $a^{-1}$ for Glaciar de Ayoloco during the same period. As documented in a photograph that had Glaciar de Ayoloco in the foreground (Melgarejo, 1910, no. 1), glacier ice surrounding *Peña Aguilera* had not yet separated into two glaciers by the summer of 1910. In views from the same photographic site, glacier ice still surrounded *Peña Aguilera* by the summer of 1918 (Paredes, 1922, figs. 11, 17, and 18). Other long-distance photographs also show one large glacier on the west side of the stomach area in 1910 (Melgarejo, 1910, no. 5; after Hugo Brehme of Mexico City). A photograph taken in April 1946, before the ablation season began, shows the possible initiation of separation into two glaciers (De Terra and others, 1949, plate 20). Historic records of the elevations of Glaciar Atzintli are not known.

Glaciar de San Agustín, which has an area of about 11,250 $m^2$, is a remnant of a once much larger niche glacier on the southeast side of the stomach area. It begins about 80 m east of the 5,070 m ridgecrest at 5,030 m and ends about 100 m to the southeast at 4,980 m (Lorenzo, 1964, fig. 41). The total area covered by all 12 glaciers on Iztaccíhuatl in 1959–60 was 1,215,850 $m^2$, about one-eighth that of the glaciers on Citlaltépetl.

Figure 7 is an enlargement of a Landsat 1 MSS false-color composite image of Iztaccíhuatl and vicinity on 7 February 1973. Although not all of the 12 named glaciers on Iztaccíhuatl can be delineated because of the spatial resolution limitations of the MSS image and because of snow cover, the three largest glaciers, Glaciar de Ayolotepito, Glaciar Centro Oriental, and Glaciar de Ayoloco can be distinguished (table 2 and fig. 5).

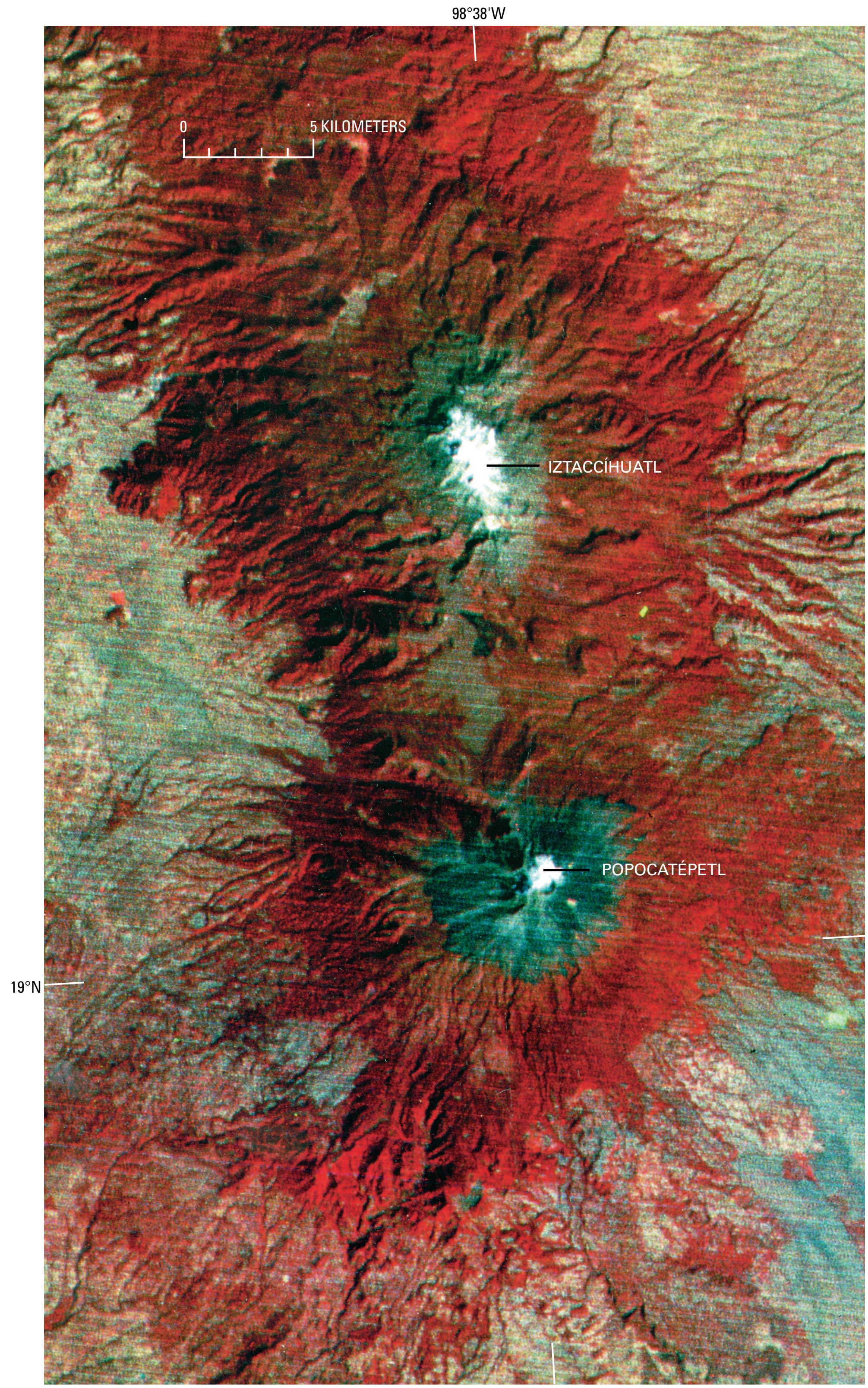



***Figure 7.***—*Enlargement of a Landsat 1 MSS false-color composite image (1199–16285; 7 February 1973; Path 27, Row 47) of Iztaccíhuatl and Popocatépetl and environs. Landsat image from the EROS Data Center, Sioux Falls, S. Dak.*

## Volcán Popocatépetl

At 5,465 m (Simkin and Siebert, 1994; previous value was 5,452 m, which is used as the reference elevation in the text for glacier elevations), Popocatépetl is the second highest peak in México and the fifth highest on the continent. It is one of the Earth's highest active volcanoes and 20 million people live within a radius of 80 km from its summit (Williams, 1999). Since 1993, intermittent explosive and occasional effusive volcanic activity has occurred from the summit of Popocatépetl (Smithsonian Institution, 1994, 1995, 1996 1997, 1998, 1999, 2000). It has one firn field that has three small glaciers flowing to the north (figs. 8 and 9 and table 3). The name is derived from the Nahuatl words, Popoca (smoking) and tépetl (mountain). The west crater rim is the highest point and is situated at lat 19º01'15" N. and long 98º37'35" W. Only 72 km southeast of Mexico City and fully visible, Popocatépetl forms the southern end of the *Sierra Nevada* at the southern geologic boundary of the North American Continent. Two Secretaría de la Defensa Nacional topographic maps are needed to provide complete coverage: Popocatépetl 14Q–h(123) and Xalinatzintla 14Q–h(124). Vertical aerial photographs taken in 1945 by Compañía Mexicana Aerofoto are available, as are oblique aerial photographs taken in 1942 and more recently by the same company.

***Figure 8.**—Glaciers on Popocatépetl. The numbers refer to the named glaciers listed in table 3. Contour interval, 100 m. (Modified from Lorenzo, 1964, sketch V.)*

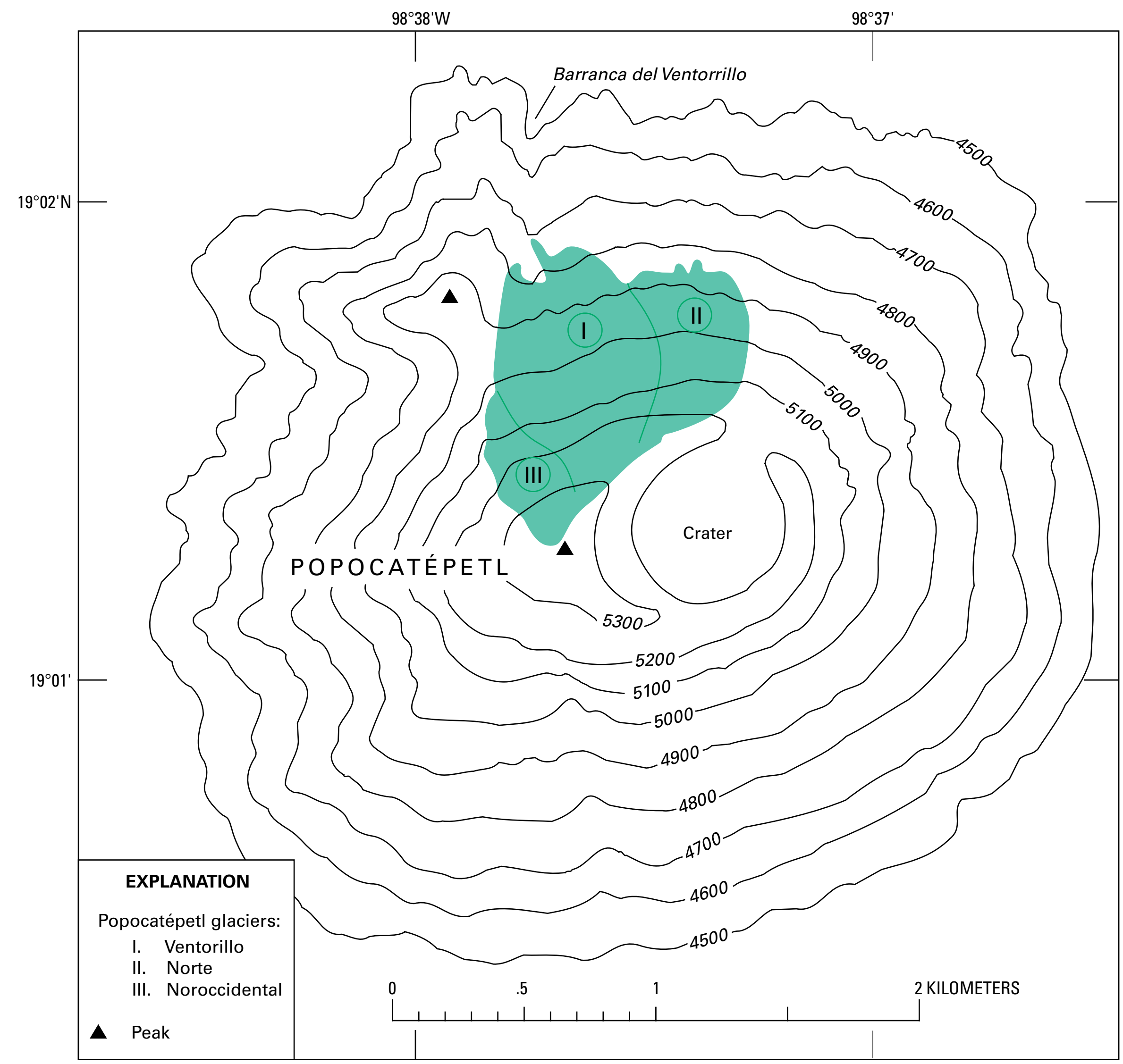


TABLE 3.—*Three named glaciers of Popocatépetl*

[Taken from Lorenzo, 1964, Sketch V]

| Glacier number | Glacier name | Glacier type | Area (square kilometers) |
|---|---|---|---|
| I | Glaciar del Ventorrillo | Mountain, firn field, valley | 0.400 |
| II | Glaciar Norte | Mountain, firn field | 0.200 |
| III | Glaciar Noroccidental | Mountain, firn field | 0.120 |
| | | Total | 0.720 |

The relative ease with which one can reach a reasonable elevation on Popocatépetl in order to start the ascent to the summit crater has always made this active volcano readily accessible. The best route is 65 km from Mexico City by Chalco, Amecameca, and up the paved mountain road to Paso de Cortés [*Paso Cortés*] at 3,680 m and then south on an excellent road 4.5 km to end at Tlamacas at 3,882 m (fig. 2) and a luxurious mountain lodge that has all facilities. Several mountain refuges are located higher up along the climbing routes on the north side. The road south of *Paso Cortés* and the refuges are closed and off limits because of the potential danger of the intermittent explosive and effusive volcanic eruptions that have been occurring from the summit crater since 1993, after a long period of quiescence since the 1940's (Smithsonian Institution 1997, no. 10). An attempt to climb Popocatépetl from the west or south sides is very difficult because from south of Amecameca, one must climb 1,700 m up the west side to 200- to 300-m-high vertical lava cliffs, which are still 1,200 m below the summit. From the south side, the climb requires a vertical ascent of 4,400 m. Any ascent from the east side from Cholula or Puebla (fig. 2) involves an ascent of about 2,300 m to the east rim at 5,193 m that also is not recommended.

Observations on the firn field and glaciers on Popocatépetl did not appear in climber's reports until the last part of the 1800's (Dollfus and others, 1867; Packard, 1886; Aguilera and Ordóñez, 1895; and Farrington, 1897), although its existence was known as early as 1519 through the writing of the historian Prescott (1872–75). During eruptions in 1920–22, glacier ice did not completely disappear because it was in a protected position in *Barranca del Ventorrillo* on the north side of the cone (Waitz, 1921) (fig. 8). White (1954) described the firn field and the glacier ice and gave elevations of one small ice tongue for 1950 and 1953. Lorenzo (1959, 1964) and his team obtained data on glacier activity, areas, and elevations, took photographs, and named the three glaciers. Much of the information that follows is from White (1954, 1981b).

A warm temperate-rainy climate without any obvious dry season rings Popocatépetl to about 3,880 m. December through March is the driest time of year; summers are short and cool on the north and west sides. September is the rainiest month, but rain falls nightly in late June and July. Valleys leaving this area carry no perennial streams from the porous and permeable slopes above. A narrow band of tundra climate circles the volcano above 3,880 m up to the ice-cap climate of the firn field and glaciers. Winter accumulation added to that of summer enables the firn field to flourish on the upper cone. The loss of firn and new snow from melting increases from January through May, the greatest loss being in May. Greater cloudiness and new snow reduce melting in June through December, except for October, when skies are clearer and precipitation is less. Maximum evaporation on the upper cone takes place from March through May. Penitentes (conical or irregularly shaped pillars of snow and ice formed by differential ablation) appear all over the cone by May (White, 1954, fig. 5). Owing to summer cloudiness, the least evaporation takes place from July through September.

The firn field on the north, northwest, and west sides of the upper cone generates three glaciers downslope, Glaciar Norte above the north volcano flanks, Glaciar del Ventorrillo in *Barranca del Ventorrillo*, and Glaciar Noroccidental above the west side cliffs (fig. 8). In 1950, the lower limit of Glaciar Norte (not recognized then as a glacier) was estimated as about 4,800 m. Lorenzo in 1958 recorded it on the convex north cone from about 5,250 m down to 4,840 m (Lorenzo, 1964, figs. 26 and 27), but he noted that it was only the remnant of a glacier. From Lorenzo's map (fig. 8), Glaciar Norte, as he then subdivided the firn field, is about 600 m long, has a gradient of 600 m $km^{-1}$, and covers about 200,000 $m^2$ of the cone.

The fluctuation of Glaciar del Ventorrillo is more significant in determining the history of the Popocatépetl firn field and glaciers. The 1945 aerial photographs show no expansion of the Ventorrillo firn edge as glaciers, but by 1949, two conspicuous but small ice tongues extended into the head of *Barranca del Ventorrillo* (White, 1954, fig. 2). In 1950, the lower ice tongue was measured as 4,573 m; in 1953, it had melted back 4 m in elevation (White, 1954, fig. 4), and in 1958, Lorenzo (1964) found it at about 4,690 m. This is a recession of 117 m in elevation over a distance of about 270 m, an average rate of retreat of about 34 m $a^{-1}$ in the 8-year interval. After 1958, the small ice tongue disappeared. In 1958, the glacier began below the north crater rim at about 5,200 m, was about 800 m long on a gradient of 640 m $km^{-1}$, and occupied about 400,000 $m^2$ of the cone (Lorenzo, 1964, figs. 26, 29, 30). This steep gradient pulls the ice apart to form huge crevasses (fig. 9). Ice on the cone above Glaciar del Ventorrillo above 5,030 m was about 40 m thick in 1951 and about 30 m thick in 1958.

Glaciar Noroccidental is the western counterpart of the other two glacier extensions of the firn field, becoming distinguished as a glacier at about 5,300 m. It ends above the lava cliffs at 5,015 m, is 440 m long on a gradient of 430 m $km^{-1}$, and occupies 120,000 $m^2$ of the cone (Lorenzo, 1964, figs. 29 and 31). In 1958, the Popocatépetl firn field and glaciers totaled only 720,000 $m^2$, about half that of Iztaccíhuatl glaciers. At the time of Lorenzo's measurements, all of Mexico's firn fields and glaciers covered about 11.4 $km^2$.

The firn field on Popocatépetl undoubtedly did not survive the "Hypsithermal Interval." Yet historic Toltec and Aztec sketches of the mountains depict much ice and snow on both Iztaccíhuatl and Popocatépetl. Cortes' captains had great difficulty crossing the perpetual snows of the Popocatépetl cone in 1519. Packard (1886) stated that in 1885 a stream flowing in the largest valley on the north side of the mountain was "fed by the snows

***Figure 9.****—Popocatépetl from the north at Tlamacas (fig. 2). A permanent firn field exists above the arcuate crevasses and icefall. Glaciar Norte is on the cone under recent snowfall above the leftmost tree. The reactivated Glaciar del Ventorrillo is visible below the crevasses as a double-lobed glacier hanging down from the cone into Barranca del Ventorrillo. Glaciar Noroccidental is on the cone at the right edge of the firn field above a sloping, castellated rock crag. Photograph taken 23 March 1978 by M.L. White.*

of the peak." No stream flows there today, even with the huge firn field above, except on sunny days when it is melting. When Anderson (1917) climbed Popocatépetl in 1906, he found a glacier in *Barranca del Ventorrillo* down to nearly 4,335 m, as estimated from his photograph (Anderson, 1917, plate XXV). Because of the clarity of detail, photographs taken in 1910 by Hugo Brehme of Mexico City disclose the glacier in *Barranca del Ventorrillo* to be at a position estimated at 4,390 m. Melgarejo's photograph (1910, no. 2), taken from Brehme's photographic site, shows the glacier at this same elevation. Weitzberg (1923, photograph 8) pictures the glacier just before the 1920–21 eruptions at about 4,435 m. In addition, Brehme's other 1910 photographs reveal thick ice or firn on the west flanks of Popocatépetl below the lava cliffs beneath Glaciar Noroccidental at approximately 4,700 m, as well as at about 4,650 m on the flanks due west of the highest summit, places where no ice or firn exists at the time of this writing.

The 100-m recession in elevation of Glaciar del Ventorrillo from 1906 to 1920 agrees with field evidence of fresh striations and glacial polish on bedrock knobs down to 4,440 m and with weathered, disintegrated, striated bedrock below 4,335 m down to 4,236 m (White, 1954). Although quite speculative and without accurate dating control, the position where Anderson found the glacier in 1906 may match the retreat from the late-neoglacial Arapaho Peak advance (Benedict, 1973) of the southern and middle Rocky Mountains in the United States. Evidence of a still older advance, certainly prior to 1519 and possibly matching the middle-neoglacial Audubon advance of the Rocky Mountains, exists where *Barranca del Ventorrillo* emerges from the steeper part of the cone (fig. 9). Here, and 100 to 200 m beyond on the gentler north flanks to 4,150 m, are striated and polished but weathered surfaces on lava flows, an end moraine almost crossing the valley floor of *Barranca del Ventorrillo*, an inner lateral moraine on the east side of the valley, and striated blocks in the tephra of a dissected alluvial fan 10 to 100 m north of the end moraine (White, 1954).

When Waitz (1921) climbed Popocatépetl in early 1921 during an eruption, he saw the glacier still well preserved in *Barranca del Ventorrillo*. He attributed this preservation to the glacier's sheltered position and the thickness of volcanic deposits on this side of the cone. Waitz estimated that the glacier then reached to about 4,800 m. How much of the recession from the 4,435 m position in 1920, estimated from Weitzberg's (1923) pictures, is due to the 1920–21 volcanic activity is not known, but growth again since 1921 down to 4,573 m in 1950 attests to a healthy positive mass balance for those 30 years. The rapid recession of 117 m in elevation from 1950 to 1958 suggests a sudden change to a negative mass balance.

The activity of the firn field on the cone above Glaciar del Ventorrillo is revealed by a 37-year study of the appearance and disappearance of crevasses. No crevasses were visible on the oblique aerial photographs of the firn field in 1942. Vertical aerial photographs taken in November 1945 show only one crevasse about 225 m long. By July 1949, four crevasses about 300 to 400 m long had appeared and were accompanied by several smaller ones. By August 1950, all but two of the larger crevasses had disappeared because of snow infilling. By May 1953, no new crevasses had appeared, and all the old ones were nearly filled by snow. By April 1955, the small ice tongues of Glaciar del Ventorrillo had retreated high onto the cone, the old but unopened crevasses of 1950 still showed, and a new set of short, en echelon crevasses had opened between Glaciar Noroccidental and the west edge of upper Glaciar del Ventorrillo. By August 1956, one new crevasse above the healed 1950 crevasses and four new ones had opened up at the head of Glaciar del Ventorrillo, and the 1955 en echelon set was being filled by snow. The firn edge above the position where the small ice tongue had been since 1949 was so thin that many rocks showed through in 1956. The set of en echelon crevasses between Glaciar del Ventorrillo and Glaciar

Noroccidental appears in Lorenzo's figure 31 that he prepared in 1958 (Lorenzo, 1964). By November 1968, three partially snow-filled crevasses on the north crater rim and one several hundred meters lower down had formed above the head of Glaciar del Ventorrillo. As a result of this crevasse study, no doubt exists as to the activity of the firn field and the importance of that gradient of 640 m $km^{-1}$ on the northwest side of the cone.

The most significant change that took place in the 10 years between 1958 and 1968 was the growth of a thick bulge of ice down into *Barranca del Ventorrillo* in the same location as the small ice tongue of 1949–58. From the 1968 photos, its lower limit is estimated at about 4,700 m and its thickness at about 30 to 40 m. By March 1978, this large bulge of ice became a broad, lobed glacier (fig. 9), probably 70 to 100 m thick, extending from the former position of Glaciar Norte to a double-lobed glacier in *Barranca del Ventorrillo* at an estimated elevation of 4,600 m. Stratification, possibly annual, of the lobes of ice reveals at least 10 layers. In the 10 years following 1968, strong drawdown by this double-lobed glacier produced four or five deep, wide crevasses just above its head and a chaotic icefall of seracs on the cone. In August 1979, the sides of this double-lobed glacier appeared as 50-m-high vertical cliffs, except where the lowest lobe at 4,600 m projected as a steep ramp into *Barranca del Ventorrillo*. A few tens of meters below the crater rim, a new, long crevasse also cut across the cone. In 1984, French volcanologists recorded the continuing existence of this same double-lobed glacier and its vertical cliffs (Christian Boudal, letter dated 24 September 1984).

Glaciar del Ventorrillo has continued to retreat because of heating, sulfur dioxide gas flux, spasmodic fumarolic activity of the volcano, and tephra falls from the main crater. The area of glaciers on the north flanks already had diminished by 24 percent from 1958 to 1982 (Delgado and Brugman, 1995; Palacios, 1996; Smithsonian Institution, 1994, 1995, 1996, 1997). Estimations of the elevation of the glacier front made by Hugo Delgado are in Palacios (1996, table 1): in 1989 at 4,680 m, in 1992 at 4,694 m, and in 1993 at 4,702 m. Palacios (1996), on the basis of his field measurements, found the glacier front in February 1994 at 4,713 m and in November 1995 at 4,735 m, as is clearly shown on his map. Delgado and Brugman (1995) measured it in April 1995 at 4,879 m. Their rate of recession between 1982 and 1995 was 7.6 m $a^{-1}$. Palacios and Marcos (1998) noted that Popocatépetl's glaciers had undergone significant retreat during the 1980's and early 1990's, a process that accelerated between 1994 and 1995.

In 1993, Popocatépetl awakened from a long period of quiescence. Since 1345, it has had 30 observed eruptions. In the 20th century, it has been active in 1920–1922, 1923–1924, 1933, 1942–1943, and 1947 (Smithsonian Institution, 1997, no. 10).

On March 5 1996, tephra dropped over the north flank and covered the snow and glaciers there; this occurred also on 30 April and again on 28–29 October 1996 (Smithsonian Institution, 1996, no. 4, 10; 1997, no. 3).

In 1997, on 20 March and 24 and 29 April, tephra was blown to 4 km above the summit and fell on the glaciers on the north slopes; one of the most violent eruptions in the past three years threw tephra all over the volcano as well as far to the east on 11 May (Smithsonian Institution, 1997, no. 4). The amount of glacier recession and ice melted by hot tephra after such events is unknown. On June 1997, the largest tephra emission of the 1994-97 eruption occurred; several large tephra emissions had also taken place earlier during May and June.

Between June 1997 and June 1999, Popocatépetl experienced an increase in seismic activity and intermittent periods of explosive and occasional effusive volcanic activity from it steep-walled, 250 m-deep summit crater (Smithsonian Institution, 1998, nos. 1, 2, 5, 6, 8, 10, 12; 1999, nos. 1, 3, 4, 6). The Centro Nacional de Prevención de Desastres (CENAPRED), Universidad Nacional Autonoma de México (UNAM), sends periodic reports to the Smithsonian Institution that are published in the monthly bulletin of the Global Volcanism Network. Up-to-date information from CENAPRED about Popocatépetl volcanic activity can be obtained from their Web site [http://www.cenapred.unam.mx/] under the heading: Boletines and Boletin del Volcán Popocatépetl. The largest explosive event during this period occurred on 20 June 1997, when a 13-km-high column of tephra arose from the summit crater. This eruption had no observable effect on Popocatépetl's glaciers (Smithsonian Institution, 1997, no. 10). However, a closer inspection in January 1998 (Sheridan and others, 2001) revealed that "…the glaciers showed noticeable ablation and lacked marginal ice cliffs that had been observed in 1995." Sheridan and others (2001) also referenced floods that originated from the terminus of Glaciar Ventorillo on 1 July 1997, that must have resulted from melting of glacier ice. In late February and early March 1999, the glaciers were observed to be partially blanketed with tephra; impacts from the December 1998 activity were visible, and runoff from melting ice and snow was evident (Smithsonian Institution, 1999, no. 3). On 15 May 1999, the increase in activity was accompanied by runoff of meltwater (Smithsonian Institution, 1999, no. 5). Low-level activity continued during July into the first part of October 1999, including occasional low-magnitude microseismic and/or tectonic events and tephra plumes and falls on 1, 5, and 29 September, and a 4-km high tephra column on 3 October 1999 (Smithsonian Institution, 1999, no. 9). On 25 February 2000, a small block-lava dome was observed to be growing in the center of the summit crater (Smithsonian Institution, 2000, no. 1). In summer 2000, two small mudflows were noted on 23 and 24 June 2000, and tephra plumes and falls took place on 3, 4, and 14 July 2000, and on 4 and 10 August 2000. The 4 August 2000 explosive event was the largest, producing a 5-km high tephra column and tephra falls on several nearby towns (Smithsonian, 2000, no. 7). Additional explosive events were reported in October 2000 (Smithsonian, 2000, no. 10). In December 2000 and January 2001, additional tephra columns were reported; on 29 January 2001, flows of pyroclastics caused some melting of glacier ice (Smithsonian, 2000, no. 12). The long-term impact by the volcanic activity on the mass-balance of Popocatépetl's glaciers must await the cessation of its currently active phase. Research by Sheridan and others (2001) stated that the glacier ice on Popocatépetl covered an area of 0.559 $km^2$ in April 1995; radio-echo-sounding surveys showed a volume of $2.8 \times 10^7$ $m^3$ of glacier ice. They postulated that about one-third of the volume ($\sim 1 \times 10^7$ $m^3$) was available for melting, primarily by ablation from pyroclastic flows. Lorenzo (1964) calculated an area of 0.720 $km^2$ (Table 3), so the loss of area is 0.161 $km^2$ or about 22 percent.

Figure 7 is an enlargement of a Landsat 1 MSS false-color composite image of Popocatépetl and vicinity on 7 February 1973. The three named glaciers can be delineated on the northwest slope of the volcano, although they are just barely within the spatial resolution of the MSS image. Snow can also be seen in the 0.8-km-wide summit crater.

# Landsat Images of the Glaciers of Citlaltépetl, Iztaccíhuatl, and Popocatépetl

Landsat MSS images are only marginally useful in delineating the termini of some of the larger individual glaciers at the summit areas of the Mexican volcanoes. The small area of these glaciers and the spatial resolution limitation (79-m pixels) of the MSS image are the limiting factors. A search of the Landsat image archive turned up two usable Landsat 3 return beam vidicon (RBV) images of the glaciers of Iztaccíhuatl and Popocatépetl; no Landsat 3 RBV images of Citlaltépetl were acquired. Unfortunately, however, the national Landsat 3 RBV archive has been destroyed. The only images that remain are in local archives, such as the Satellite Glaciology Project at the U.S. Geological Survey. Figure 10 is an enlargement of the December 1980 Landsat 3 RBV image of Iztaccíhuatl and Popocatépetl. When compared with figure 7, a Landsat 1 MSS false-color composite image of the same area, it is evident that the nearly threefold increase in spatial resolution of the Landsat 3 RBV image (30-m versus 79-m pixels) permits a more reliable delineation of the firn areas and termini of the 12 glaciers on Iztaccíhuatl and 3 glaciers on Popocatépetl. Table 4 provides a list of the optimum Landsat 1, 2, and 3 images of the glaciers of México; figure 11 is an index map showing the location and coverage of the optimum Landsat imagery.

TABLE 4.—*Optimum Landsat 1, 2, and 3 images of the glaciers of México*

[see fig. 11 for explanation of symbols used in “code” column]

| Path-Row | Nominal scene center (lat-long) | Landsat identification number | Date | Solar elevation angle (degrees) | Code | Cloud Cover (percent) | Remarks |
|---|---|---|---|---|---|---|---|
| 26–47 | 18°45'N. 96°53'W. | 1180–16225 | 19 Jan 73 | 38 | ● | 0 | Citlaltépetl |
| 26–47 | 18°45'N. 96°53'W. | 1306–16231 | 25 May 73 | 61 | ● | 0 | Citlaltépetl, image used for figure 4 |
| 26–47 | 18°45'N. 96°53'W. | 21508–16003 | 10 Mar 79 | 44 | ● | 0 | Citlaltépetl |
| 27–47 | 18°45'N. 98°19'W. | 1199–16285 | 07 Feb 73 | 41 | ● | 0 | Iztaccíhuatl and Popocatépetl, image used for figure 7 |
| 27–47 | 18°45'N. 98°19'W. | 1235–16291 | 15 Mar 73 | 51 | ◕ | 10 | Iztaccíhuatl and Popocatépetl |
| 27–47 | 18°45'N. 98°19'W. | 31028–16054-A | 27 Dec 80 | 34 | ● | 0 | Iztaccíhuatl and Popocatépetl, image used for figure 10; Landsat 3 RBV image archived by the USGS Satellite Glaciology Project |

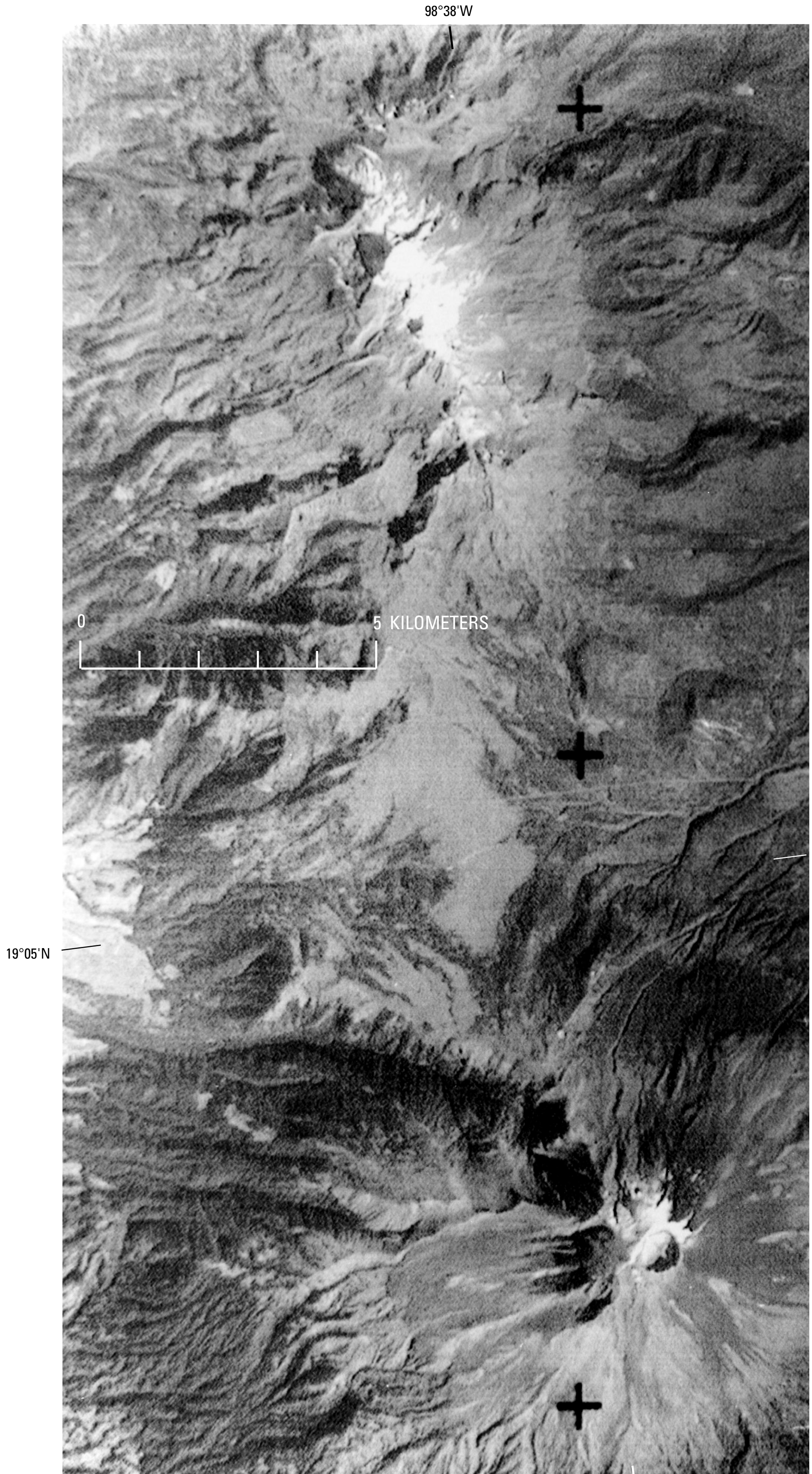
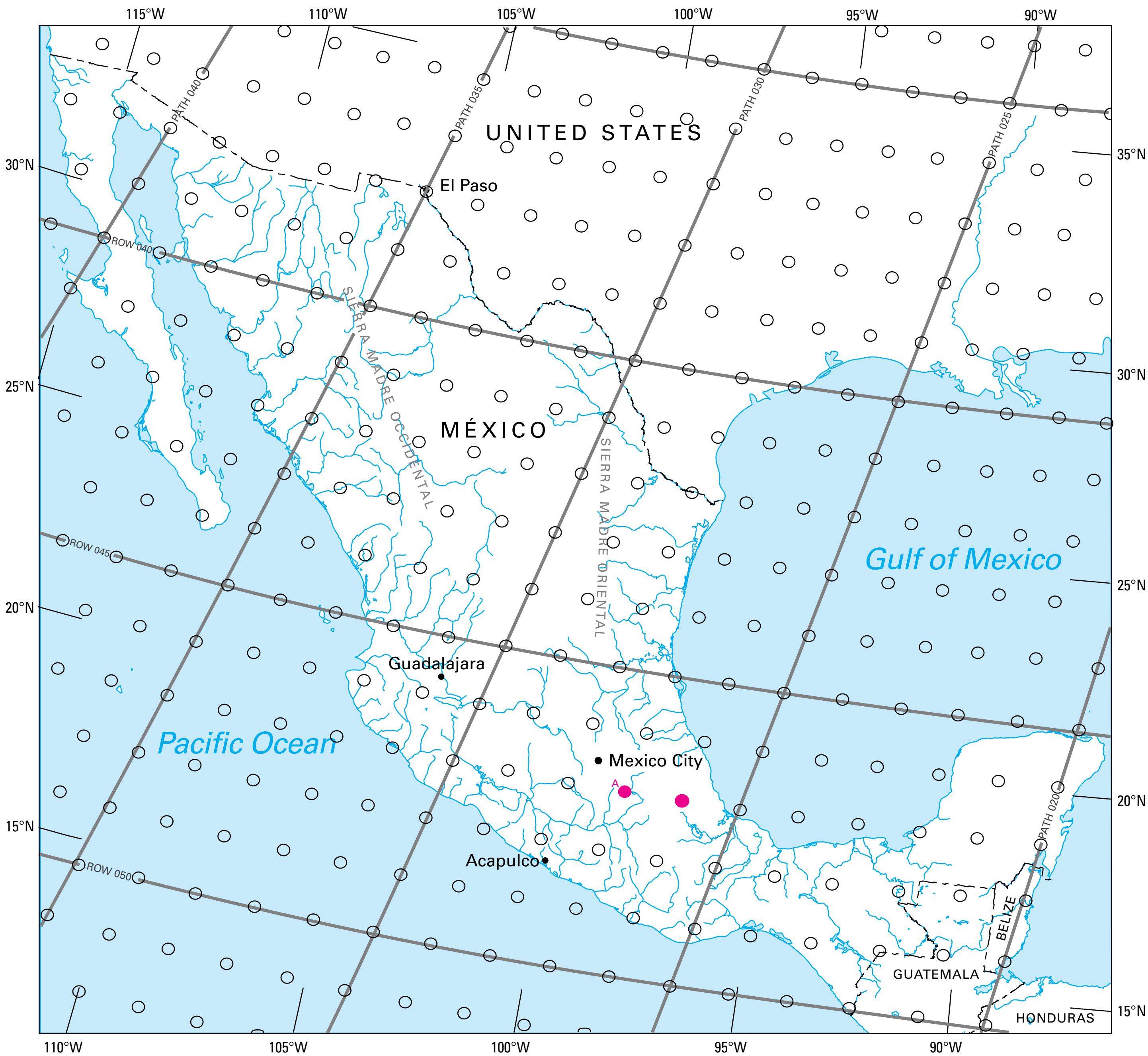



***Figure 10.***—*Enlargement of a Landsat 3 RBV image (31028–16054, subscene A; 27 December 1980; Path 27, Row 47) of the glaciers and firn on the summit areas of the Iztaccíhuatl (north) and Popocatépetl (south) volcanoes. Reproduced by permission of the Earth Observation Satellite Company (EOSAT).*




0 400 KILOMETERS

EXPLANATION OF SYMBOLS

Evaluation of image usability for glaciologic, geologic, and cartographic applications. Symbols defined as follows:

- Excellent image (0 to ≤5 percent cloud cover)
- A B C D — Usable Landsat 3 RBV scenes. A, B, C and D refer to usable RBV subscenes
- Good image (>5 to ≤10 percent cloud cover)
- Nominal scene center for a Landsat image outside the area of glaciers

***Figure 11.****—Optimum Landsat 1, 2, and 3 images of the glaciers of México.*

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