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Research paper

Impact of the eruptive activity on glacier evolution at Popocatépetl Volcano (México) during 1994–2004

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Abstract

Distribution, rate and magnitude of the glacier changes caused by eruptive activity over 1994–2001 at Popocatépetl Volcano were determined. Digital-elevation models computed by scanned photographs within a digital photogrammetric workstation and the subsequent DEM comparison allowed the determination of glacial changes. The results show that drastic changes occurred in glacier geometry and morphology over 1996–2001: 53% of the glacier surface area was lost due to melting processes. The most important loss occurred over 2000–2001 when 19% of the glacier-covered area disappeared. The glacier volume losses increased over time; during 1999–2000 the largest loss was observed. However, in February 2001, the glacier showed an apparent small increase in volume. Volcanic processes disturbed the mass balance of the glacier, thereby accelerating the ablation processes. The eruptive behavior of Popocatépetl was characterized during this time by alternating periods of explosive events and low activity. Pyroclastic flow generation, ejection of incandescent material, and tephra fall affected the glacier. The tephra volume, distribution and remobilization produced considerable changes on glacier evolution. Tephra deposition on the glacier surface was the most frequent process. The irregular distribution and thickness of tephra provoked differential ablation, and tephra remobilization processes took place on the glacier surface. Together, these processes incised the glacier surface over time. Based on these results and observations, a model of glacier evolution is proposed, involving an adjustment phase, thinning phase, areal-retreat phase, and fragmentation phase. A complex interplay of factors and processes took place between eruptive activity and the glaciers at Popocatépetl Volcano. The glacier evolution and subsequent extinction were induced by the eruptive behavior over the years. While not the only process at work, eruptive activity played the primary role in accelerating retreat and as a consequence in glacier extinction.

Keywords: Popocatépetl Volcano; ice-clad stratovolcano; volcano-ice interactions; digital photogrammetry; glacier retreat

1. Introduction

Interactions between eruptive activity and glacier dynamics on ice-clad stratovolcanoes vary over a wide spectrum. They depend on the eruptive behavior and glacier characteristics in different timescales. In some cases, high-intensity eruptions occur in a short span of time (hours to days), provoking immediate drastic changes in glacier geometry, morphology and dynamics. For instance, during the 1980 eruption at Mount St. Helens, 70% of the total volume of ice was removed (Brugman and Meier, 1981). During the 1985 eruption at Nevado del Ruíz, Colombia, the eruption melted, fractured and destabilized the ice cap (Thouret, 1990). On the other hand, eruptions characterized by intermittent eruptive activity of variable, moderate intensity act over years or decades, producing gradual changes on the glaciers. In the 1995–1996 eruptive episode of Mount Ruapehu, New Zealand, sub-plinian eruptions deposited thick tephra layers on ice and seasonal snow, resulting in complex post-eruptive interactions of tephra, snow and liquid water (Manville et al., 2000). In general such changes are, less dramatic but equally important and more difficult to document.

After 10 years of eruptive activity at Popocatépetl Volcano, its glaciers have changed their geometry and morphology dramatically. To identify the operative processes, a multitemporal

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analysis based on the photo-derived digital elevation models (DEM) reveals the distribution, rate and magnitude of the glacial changes. This study documents the impact of the eruptive activity on the glacier evolution and proposes a corresponding model.

2. Recent eruptive activity

Initial signals of reawakening such as increasing seismic activity, SO_2 emission, fumarolic activity, and a decrease of pH in the crater lake waters were observed at Popocatépetl since 1993 (Goff et al., 1998; Delgado-Granados et al., 2001). The eruptive activity at Popocatépetl has been intermittent and fluctuating as shown by the number of explosions (Fig. 1). The current eruptive period began on December 21, 1994, with intense seismic activity, followed by explosions forming a 7 km-high ash column and producing ash fallout extending 50 km from the source towards the east and north. The strongest eruptive phase occurred from December 24 to 25, after a brief eruptive activity decline. During January–March 1995, intermittent explosions occurred. By August 1995, the eruptive activity decreased markedly and the explosions ceased through February 1996. On March 5, 1996 a vulcanian explosion again generated emissions of ash, and by March 25 a lava dome was extruded in the crater (Delgado-Granados et al., 2001). The lava emission decreased gradually in July, and by September dome growth stopped. Strong explosions occurred on October 28, November 27, and December 5, the related eruption columns reached 10 km in height and generated small pyroclastic flows. Finally, on December 29, 1996, an explosion destroyed the lava dome (CENAPRED), ending the first dome growth-destruction phase.

Intense explosive phases occurred from November 1998 to early January 1999 and throughout October 2000 to May 2001. They were characterized mainly by emission of gases and ash, ejection of incandescent material (ballistics), and, less commonly, pyroclastic flows. The number of explosions over 1999 and 2000 were scarce. However, eruptive events of short duration and low explosivity-characterized by reduced gas emission, and minor ash have been the most frequent during the eruptive period (1996–2001) (CENAPRED). Table 1 shows a summary of the eruptive activity at Popocatépetl.

3. The state of glaciers previous to December 1994

The glaciers of Mexico are situated in the intertropical zone (approximately 19° N) and their existence is a result of temperature, precipitation, elevation, and aspect. The glaciers at Popocatépetl were nested on the northern slope of the volcano (Fig. 2). The first glacier inventory, made by Lorenzo in 1958, documented three glaciers covering an area of 0.729 km^2 (Lorenzo, 1964): Glaciar Noroccidental (GN), Glaciar del Ventorrillo (GV) and Glaciar Norte.

Delgado-Granados (1997) updated Lorenzo's glacier inventory, reporting 0.559 km^2 of glacier-covered area and characterizing the glaciers in 1982. The GV was a mountain glacier with an elevation range of 4760–5380 masl, an estimated thickness of 50 m in the deepest parts, two transversal crevasse systems, and drainage to the northeast through the Huiloac Gorge. GN was a small glaciarette with an elevation range of 5060–5400 masl located to the west of GV (Fig. 2), made by ice and ash (black ice), and without crevasses. The Glaciar Norte was recognized as a part of the GV. Taking into consideration the location and size of GV and GN, hereafter we will refer to both glaciers simply as the "glacier".

The regime of Popocatépetl's glacier used to be characterized by two periods of accumulation: summer (June to August) and winter (December to February) when the maximum

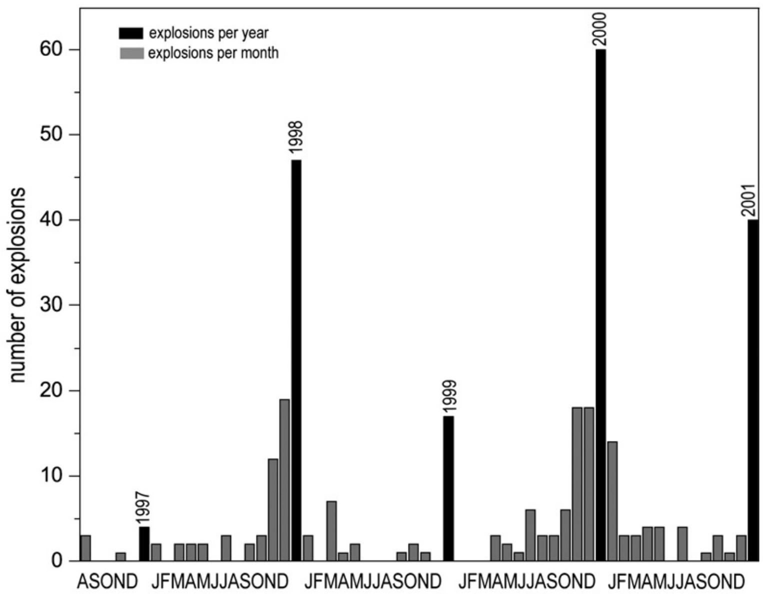

Fig. 1. Number of explosions at Popocatépetl Volcano from August 1997 to February 2001. The graph shows explosions that produced ash columns ≥ 1 km high. The data were obtained from eruptive activity daily reports of CENAPRED and observations of the authors.

Table 1
Chronology of the 1993–2001 volcanic activity at Popocatépetl Volcano. The table was prepared from eruptive-activity daily reports of CENAPRED, aerial photographs, and data in Delgado-Granados et al., 2001. The asterisk indicates the date of the photographs used in the present study

Date	Event
1993	Previous activity: increase of seismic activity, SO_2 emission and pH of crateric lake
1994	
21 December	Activity started. Intense seismic activity, ash column rose 2 km and reach several towns E and NE, including Cities of Puebla and Tlaxcala
1995	
13 February	Explosions, eruption column 4 km height
31 March	Explosions
06 April	Explosions
05 October	Explosions, ash fall at Puebla City
1996	
05–07 March	Increase of seismic activity, explosions
25–27 March	Explosions and lava emission at the inner crater
26 May	Dome*
27–31 October	Explosions destroyed partially the lava dome, eruption column 2–3 km height
21 November	Dome
27 November	Explosions, ash fall at Puebla City (40 km, E)
11 December	Depression at the inner crater
29 December	Explosions, ejection of fragments
1997	
17–19 January	Lava emission at the inner crater
28 February	Depression at the inner crater
12 March	Explosions
19 March	Explosions, eruption column 3 km height
24 April	Explosions, eruption column 4 km height and lava emission at the inner crater
29 April	Explosions, ash fall at Puebla City
07 May	Explosions, eruption column 2 km height, local ash fall
11 May	Explosions, ash fall at Puebla City
14 May	Explosions, ejection of incandescent material, local ash fall, bush fires were observed
11 June	Explosion, eruption column 9 km height, ash fall at Puebla and Cholula, depression at the inner crater
30 June	Explosion, eruption column 10 km height, ash fall at México City (70 km, SW), pyroclastic flows at S and SE flanks
01 July	Lahar flow down at Huiloac Gorge
04 July	Dome
12 August	Explosion, eruption column 2 km height
19 August	Lava emission at the inner crater
22 October	Dome
14 November	Dome and gases in the crater
24 December	Explosion, ejection of incandescent fragments, bush fires were observed
1998	
01 January	Explosion, eruption column 6 km height, ejection of incandescent material
16 January	Depression in the inner crater
17 March	Depression in the inner crater
21 March	Explosion, eruption column 2 km height, ejection of incandescent material at NE and NW to 3 km, ash fall at Puebla City
12 April	Flows at NE flank
21 April	Explosion, eruption column 4 km height, ejection of incandescent material, bush fires
27 April	Explosion, eruption column 4 km height
08 June	New dome in the crater
14 August	Explosion, eruption column 3–4 km, local ash fall
16 August	Explosion, eruption column 2–3 km, ash fall at NW sector
24 August	Depression at the crater, no dome
21–23 September	Multiple explosions, eruption columns 3–4 km height, local ash fall
05 October	Explosion, eruption column 4 km height
17 October	Explosion, ash fall at south of México City
19–30 November	Multiple explosions, eruption columns 1–4 km height, ejection of incandescent material to 1.5–3 km
1–18 December	Multiple explosions, eruption columns 1–5 km height, ejection of incandescent material to 3 km, fires
22–23 December	Explosions, eruptions columns 1–2 km
1999	
27–30 January	Multiple explosions, eruption columns 3 km height
02 February	Depression in the crater*
08 March	Explosion, eruption column 5 km height
9–12 March	Explosions, eruption columns 1–5 km height, ejection of incandescent material
18 March	Explosion, it was hearing at Amecameca, plume to 16 km N–NW
15 April	Explosion, eruption column 3.5 km height
16 May	Explosion, eruption column 2.5 km height
07 July	Flows at gorges on N sector
14 July	Depression in the crater
5 y 20 September	Explosion
21 September	Depression in the crater
3 y 31 October	Explosion
2000	
01 January	Depression in the crater*
03 April	Explosion, eruption column 2 km height
17–18 April	Explosions, eruption columns 1.5–2 km height
23 May	Explosion, eruption column 5 km
27 May	Dome in the crater
06 June	Explosion, eruption column 6 km height, ash fall in towns of Edo. México
18–19 June	Explosions, ash fall at Amecameca and Ecatzingo
3–4 July	Explosions, eruption column 1–2.5 km height, local ash fall W flank
7 y 10 July	Explosions
14–21 July	Explosions, eruption column 1–2 km height
04 August	Explosions, eruption column 5 km height, ash fall in towns of Edo. México
10 August	Explosion, eruption column 3.5 km height
2–3 September	Explosions, eruption column 3 km height, ash fall south México City
11–12 September	Explosions
15 September	Dome
23–24 September	Explosions, local ash fall
2–4 October	Explosions, eruption columns 1–6 km height
3 October	Dome
6–9 October	Explosions, local ash fall

Table 1 (*continued*)

Date	Event
16 October	Explosions, eruption columns 2 km height, ejection of incandescent material to 1 km NE
28–29 October	Explosions, eruption columns 2–3 km height, plume to 25 km
02 November	Explosion, eruption column 3 km height
6–7 November	Explosions, eruption column 1–2 km height, local ash fall
09 November	Explosions, eruption column 5 km height, plume 40 km NE
11–22 November	Explosions, eruption columns 4 km height
27–29 November	Explosions, eruption columns 1.5–3 km height
1–4 December	Explosions
12 December	Explosion, ejection of incandescent material, eruption column 5 km height, plume 80 km,
13–28 December	Explosions, eruption columns 1–4 km height, ejection of incandescent material to 2 km, local ash fall
16 December	Dome
2001	
1–5 January	Explosions, eruption columns 1–3 km height, ash fall Cholula and Puebla Cities
20 January	Depression in the crater
22 January	Explosion, eruption column >8 km height, ejection of incandescent material to 1 km NE, ash fall at Xalitzintla, Atlixco y Puebla. Pyroclastic flown down on the glacier area, lahar was generated and flown by Huiloac Gorge
23–25 January	Explosions, eruption columns 2–3 km height, local ash fall
26–30 January	Moderate explosions
13 February	Explosion, eruption column 2 km, ejection of the material incandescent to 1 km
21 February	Depression in the crater

accumulation took place. Accumulation consists predominantly of snow and hail (Delgado-Granados, 1997). Ablation was present throughout the year, but mainly during spring (March to May), when the maximum evaporation (White, 1954) and sublimation (Delgado-Granados, 1997) occur. The accumulation and ablation zones can not be clearly delineated due to the small size of the glacier. Accumulation and ablation processes took place across the entire glacier surface. Measures of ice temperature showed a range −1.5 to 0.5 °C and thus, the glacier at Popocatépetl was considered a temperate glacier.

The glacier of Popocatépetl showed a retreat trend even before the eruptive activity began in 1994. The causes for this retreat were attributed to regional and global climate change, as well as possible heat flux increase (Delgado-Granados and Brugman, 1996; Delgado-Granados, 1997). Comparison of glacier-covered area reported for 1958 (Lorenzo, 1964) and 1982 (Delgado-Granados, 1997) indicate that 22% of the glacier area had disappeared over 24 years. Variations in elevation of GV's front have been documented since 1906 (Waitz, 1921; Weitzberg, 1923; White, 1954; Lorenzo, 1964; White, 1981; Palacios, 1996; Delgado-Granados, 1997). These studies also show the retreat trend, although the position of the glacier's front has been inferred in several ways, such as aerial photographs, maps, or historical descriptions, and selective field observations. No previous published data exist for glacier volume changes.

4. Methodology and data

Generation of digital elevation models (DEM) of a glacier for different dates by digital photogrammetry allows a multitemporal analysis of the glacier changes. By DEM comparison, determination of changes of the glacial surface, volume differences, glacier mass balance can be determined (Kääb 2000). Additionally, it allows the study of areas with access difficulties or at risk (Fox and Nuttall, 1997).

Given the small glacier size and the hazards of fieldwork due to eruptive activity, several pairs of appropriately scaled aerial photographs were used for a digital photogrammetry-based study of Popocatépetl. The photographs analyzed were taken on May 21, 1996; March 16, 1997; February 02, 1999; January 08, 2000 and February 21, 2001. No adequate photographs were found for 1998. The 1999 photographs showed a meteorological cloud southwest of the glacierized area, which introduced minor errors in the DEM.

A set of 9 ground control points (GCPs) was employed (Fig. 3), seven of which were provided by the Ministry of Communications and Transport (SCT). Other GCPs were determined using the photomap of Popocatépetl Volcano (scale 1:20000). The GCPs projection is UTM, zone 14Q and the datum employed was NAD (27) Mexico (Table 2). Due to eruptive activity, the identification of GCPs located near the crater was difficult, and some of the initial GCPs disappeared over time. Five digital elevation models (DEM) were computed from scanned photographs within a digital photogrammetric workstation, afterwards the DEMs were subtracted. The accuracy of Popocatépetl's DEMs is less than those generated under more favorable conditions, owing to factors such as rough terrain, shadows, modification or disappearance of GCPs due to eruptive activity. An accuracy of up to 0.1% of the flight height above ground can be expected for elevation measurements (Huggel and Delgado-Granados, 2000). Here the accuracy of elevation changes is estimated as ±2.7 m (1996), ±3.5 m (1997), ±4.1 m (1999 and 2001), ±3.9 m (2000).

5. Results

5.1. Surface-area changes

The rate of changes in glacial surface area at Popocatépetl Volcano shows a gradual increase over time (Table 3). From 1996 to 1999, 24% of the 1996 glacier-covered area disappeared. The loss increases slightly for the period 1999–2000. For this period, 10% of the 1996 glacier-covered area was removed. Notwithstanding, the most important retreat occurred during 2000–2001, when 19% of the 1996 surface area of the glacier disappeared. The major loss took place in the frontal and eastern borders (Fig. 4).

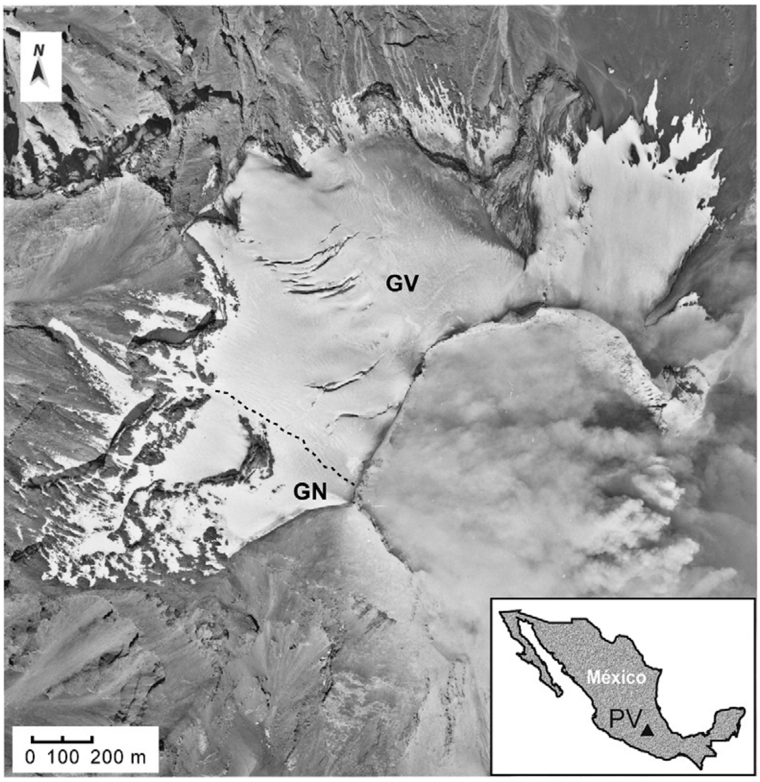

Fig. 2. The glaciers of Popocatépetl Volcano are located on the northern and northwestern flanks. This aerial photograph shows the Ventorrillo (GV) and Noroccidental (GN) glaciers on December 6, 1993. GV covers most of the area, its crevasses and main tongue are well seen.

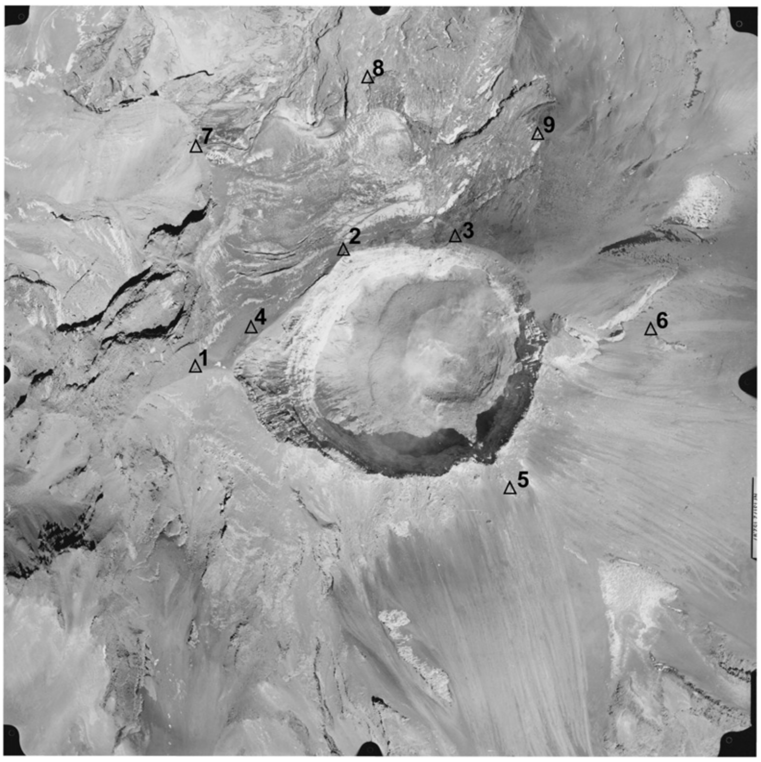

Fig. 3. Localization of the ground control points (GCPs) used to exterior orientation during the image processing at Popocatépetl. The black triangles indicate GCPs (for coordinates see Table 2).

Table 2
Ground control points (GCPs) employed to exterior orientation in image processing at Popocatépetl (for location of GCPs see Fig. 3)

GCPId	Latitude N	Longitude E	Elevation
1	2,103,168.255	539,094.116	5393.813
2	2,103,521.745	539,419.057	5273.992
3	2,103,610.998	539,722.148	5202.025
4	2,103,278.510	539,214.832	5383.603
5	2,103,438.600	540,441.500	4896.544
6	2,102,895.545	539,968.113	5139.924
7	2,104,040.000	538,700.000	5000.000
8	2,102,960.000	539,840.000	5180.000
9	2,104,100.000	540,000.000	4830.000

5.2. Volume changes

In this study, the term mass balance is not used in a strict glaciological sense. Under normal conditions, a positive mass balance means that the glacier gained more mass than it lost. A negative mass balance indicates a loss of mass over the balance year (Benn and Evans, 1998). The volumetric change estimate based on DEM subtraction corresponds to the glacier mass balance, including the tephra and snow deposited on the glacier, snow-ice density and crevasse density as well as the ice melting. This is assuming the height of the bed of the glacier does not change with time and basal cavities are negligible. The glacier mass loss, however, was large enough to result in negative mass balance. The obtained mass balance is a minimum figure for the real ice mass loss and so, we assume here these volumes as ice mass loss.

The changes in glacier volume estimated from DEM subtraction are shown in Table 3. Throughout 1996–1997, a small volume of ice and snow was lost, at a rate of 9×10^4 m^3/yr. During 1997–1999 the volume loss increased at an order of magnitude. However, the main loss occurred in 1999–2000, when the mass loss had a rate of 138×10^4 m^3/yr. In contrast, an apparent increase in volume occurred over 2000–2001. As seen later, this volume increase was linked to eruptive activity.

5.3. Morphological glacier changes

Between 1996 and 1997, the glacier surface was thickening at the frontal part as well as in small areas at the center and at the western edge (Fig. 5a); the surface thinned in the medial and upper portions. The areas with the greatest thickness, in the medial part, showed a linear pattern parallel to the upper border. About half of the glacier-covered area did not show important changes. During 1997–1999, almost the entire glacier surface showed thinning (Fig. 5b), especially at the front, the southwestern sector, and along the linear pattern observed in the previous map. The upper border showed minor changes, although at the southwestern edge the surface showed uplift. Over 1999–2000, the surface subsided, as with previous patterns (Fig. 5c). In contrast, between 2000 and 2001, the glacier surface rose, mainly at the upper part due to tephra deposition, whereas in most of the northern areas near the steep-sloping terminus, the surface subsided due to ablation (Fig. 5d).

6. Impact of the eruptive activity on glacier

The glacier at Popocatépetl Volcano disappeared as a result of the general retreat shown before the current eruption began but strongly enhanced by eruptive activity (Julio-Miranda and Delgado-Granados, 2003). The volcanic processes disturbed the mass balance of the glacier, accelerating the ablation over this time, combined with a scarce accumulation enhancing the ice loss. The eruptive behavior of Popocatépetl was characterized by alternating explosive events and low-activity phases. Pyroclastic flow generation, ejection of incandescent material, but mainly tephra fall impacted the glacier during the period 1996–2001.

6.1. Pyroclastic flows

Pyroclastic flows have been sporadic, but they occasionally have triggered lahars. By January 22, 2001, pumiceous pyroclastic flows overran the glacier-covered area, triggering a lahar. The lahar deposit (2.4×10^5 m^3 in volume) included more than 50% pumiceous material (Julio-Miranda et al., 2005). This lahar flowed 14 km down Huiloac Gorge, reaching the outskirts of the village of Santiago Xalitzintla. Surprisingly, the pyroclastic flow phase of this explosive event did not cause important changes on glacial geometry or morphology. Same phenomenon occurred on upper portion of glaciers at Mt. St. Helens, and Shoestring upper glacier and Swift actually advanced in 1981–1982 (Brugman and Meier, 1981).

6.2. Incandescent material

Highly explosive events have occurred during 1994–2001, characterized by ejection of incandescent material. In this study, incandescent material is a term applied to the volcanic material of diverse grain size, whose high temperature exhibits incandescence at night; such material ejected during explosions and followed nearly parabolic trajectories (Alatorre-Ibargüen-goitia et al., 2006). This hot material is seen as volcanic debris covering the glacier-covered area.

Table 3
Surface area and volume glacier changes at Popocatépetl (1996–2001)

Date	Surface area (m^2)	Period	Glacier area loss (m^2)	Areal lost rate (m^2/year)	Volume change (m^3/year)	Volume change rate (m^3/year)
1996-05-21	5.5×10^5					
1997-03-16	5.1×10^5	1996–1997	-4.6×10^4	5×10^4	-8.1×10^4	-9×10^4
1999-02-02	4.2×10^5	1997–1999	-8.6×10^4	4.5×10^4	-188×10^4	-100×10^4
2000-01-08	3.7×10^5	1999–2000	-5.7×10^4	6.1×10^4	-128×10^4	-138×10^4
2001-02-21	2.6×10^5	2000–2001	-11×10^4	9.4×10^4	3.1×10^4	2.8×10^4

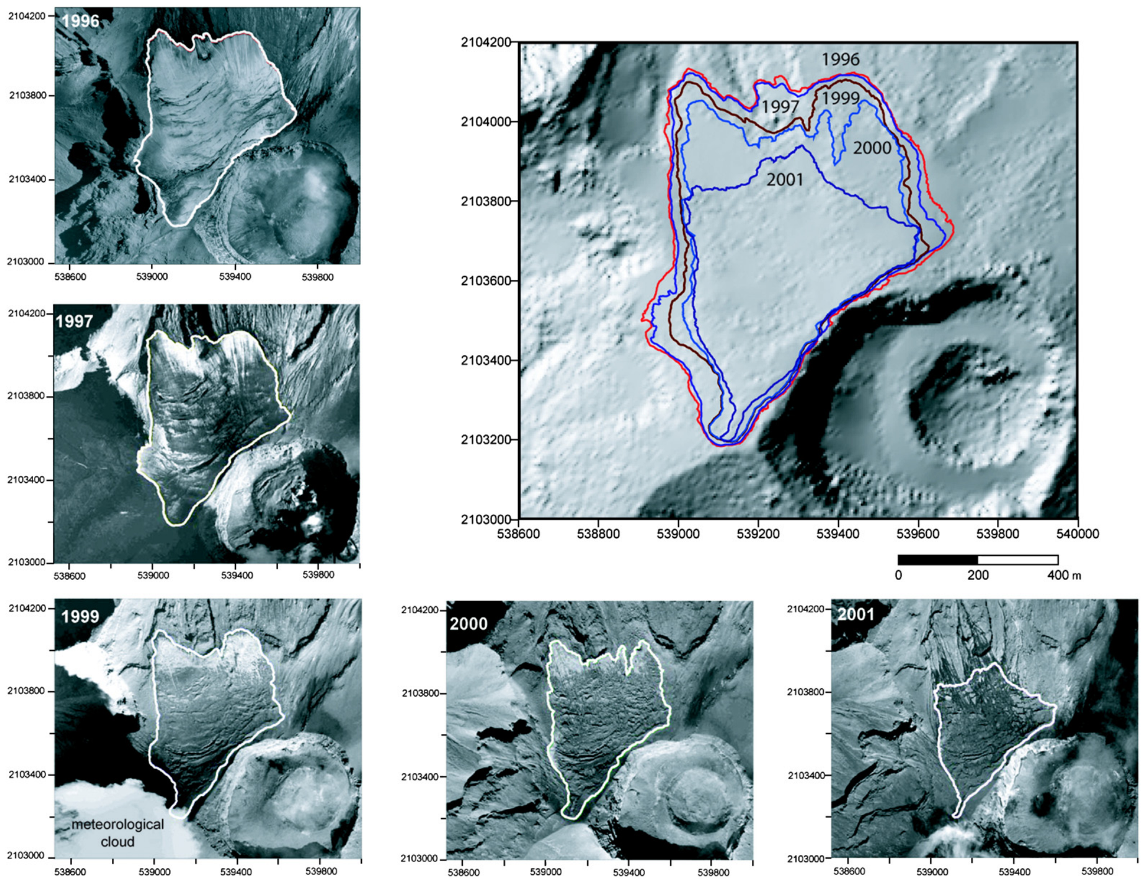

Fig. 4. Glacier-covered area changes at Popocatépetl Volcano. The shaded relief shows the glacial boundaries from 1996 to 2001. Orthophotos for each year are shown. The coordinates are UTM.

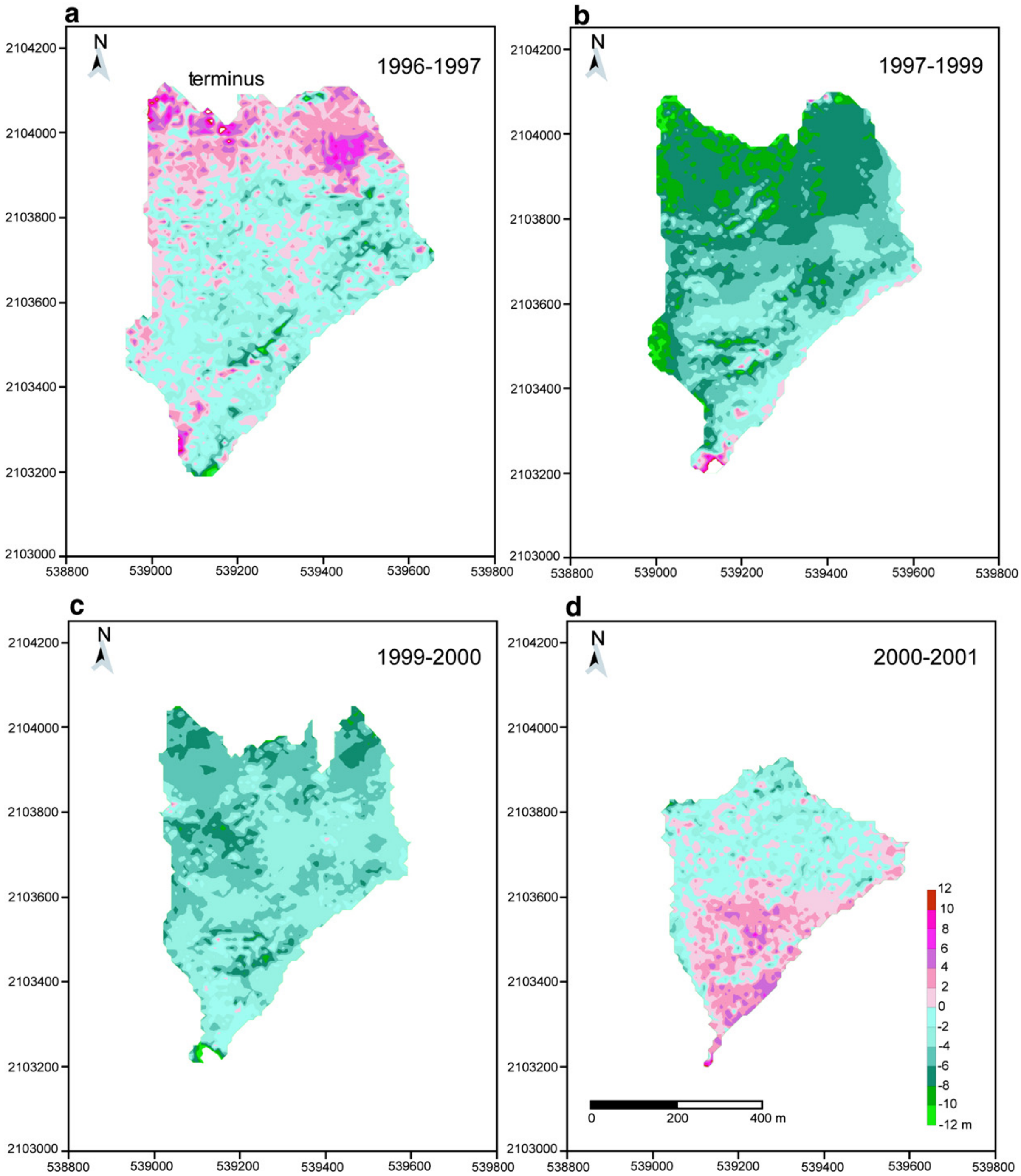

Fig. 5. Changes of glacier surface at Popocatépetl Volcano obtained from DTM subtraction 1996 to 2001. The contours represent pixels (areas) with the same uplift or subsidence in meters. The coordinates are UTM.

According to Pierson (1989), a layer of hot pyroclastic debris deposited on snow or ice produces passive melting, which is enhanced by an abundance of lithic clasts. Passive melting is slower than melting by abrasion or mixing, but it can be sustained for longer time. During explosive phases at Popocatépetl, incandescent material was repeatedly ejected upon the volcano's flanks (Fig. 6) out to 4 km from the crater, provoking melting on glacier surface and triggering brush fires on the volcano's lower slopes. As the glacier became gradually buried by tephra, the surficial melting due to the incandescent material was diminished.

The effects of the volcanic ballistic projectiles associated with explosive events of January 27 to 30, 1999, are shown in the aerial photograph taken on February 02, 1999 (Fig. 7). The glacial surface was covered by tephra, except at the frontal part, where numerous holes or impact craters produced by the ballistics could be distinguished. The holes were generated by the effects of impact of the ballistics followed by punctual

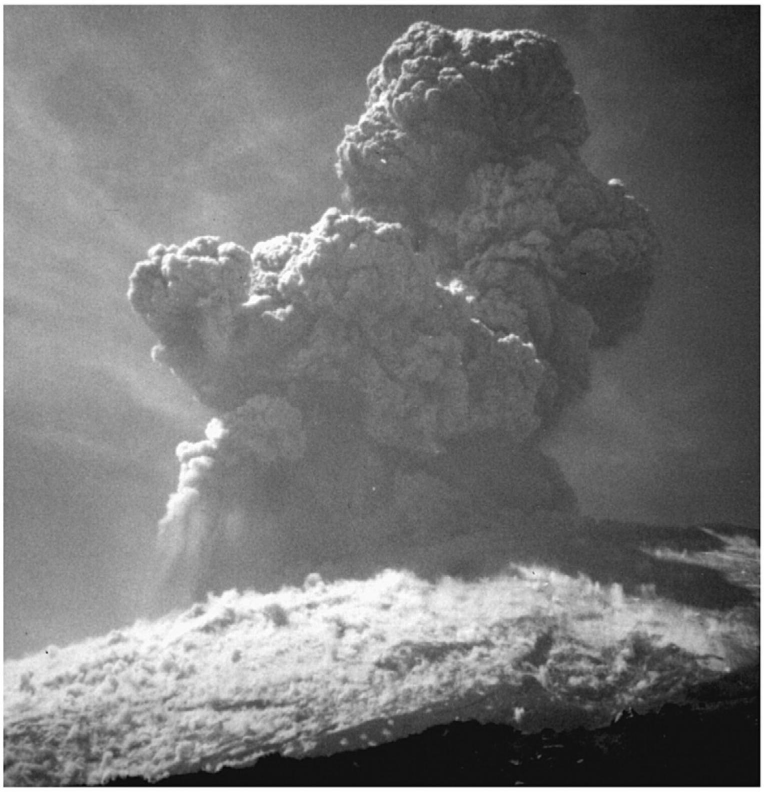

Fig. 6. Hot ballistics impact the glacierized area during an explosion at Popocatépetl Volcano, generating vapor due to melting of the glacial surface. Photograph taken by Enrique Guevara Ortiz on January 27, 1999.

ablation. The melt water saturated the tephra and generated small slurry flows on the glacial surface. After the craters were generated on the glacier, the holes increased in size due to daily ablation at their borders and walls, due to enlargement of the exposed areas. Afterwards, these craters were filled by tephra or snow, and some disappeared but others were preserved and could be observed few years after their formation.

6.3. Tephra fall

The tephra volume, distribution and remobilization produced considerable changes in glacier evolution. Tephra deposition on the glacier surface was the most frequent process. Thin layers of tephra were deposited on the surface even during the non-explosive phases by drifting wind, while during intense

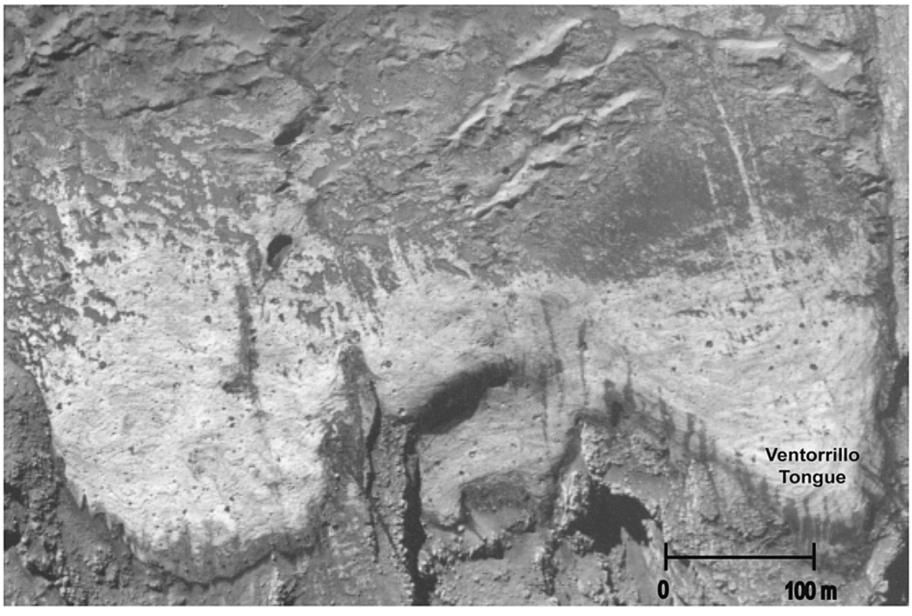

Fig. 7. The black dots on glacial tongues are holes generated by the impact of hot ballistics. Passive melting generated enough water to generate slurry flows.

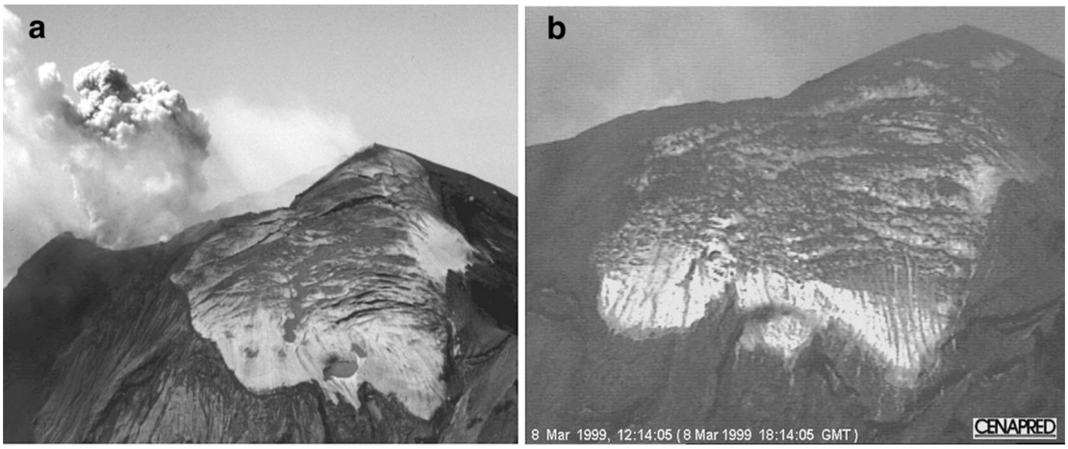

Fig. 8. Tephra distribution was determinated by the glacier morphology. 8a. Lower areas at glacial surface show larger tephra accumulation. Photograph taken by Hugo Delgado-Granados in 1997. 8b. Glacial surface is covered by tephra during the ablation season. Intense ablation generated slurry flows over the glacial surface. A band of material was deposited by tephra remobilization over glacial surface beyond the frontal margin of glacier. The image was taken on March 8, 1999 (CENAPRED).

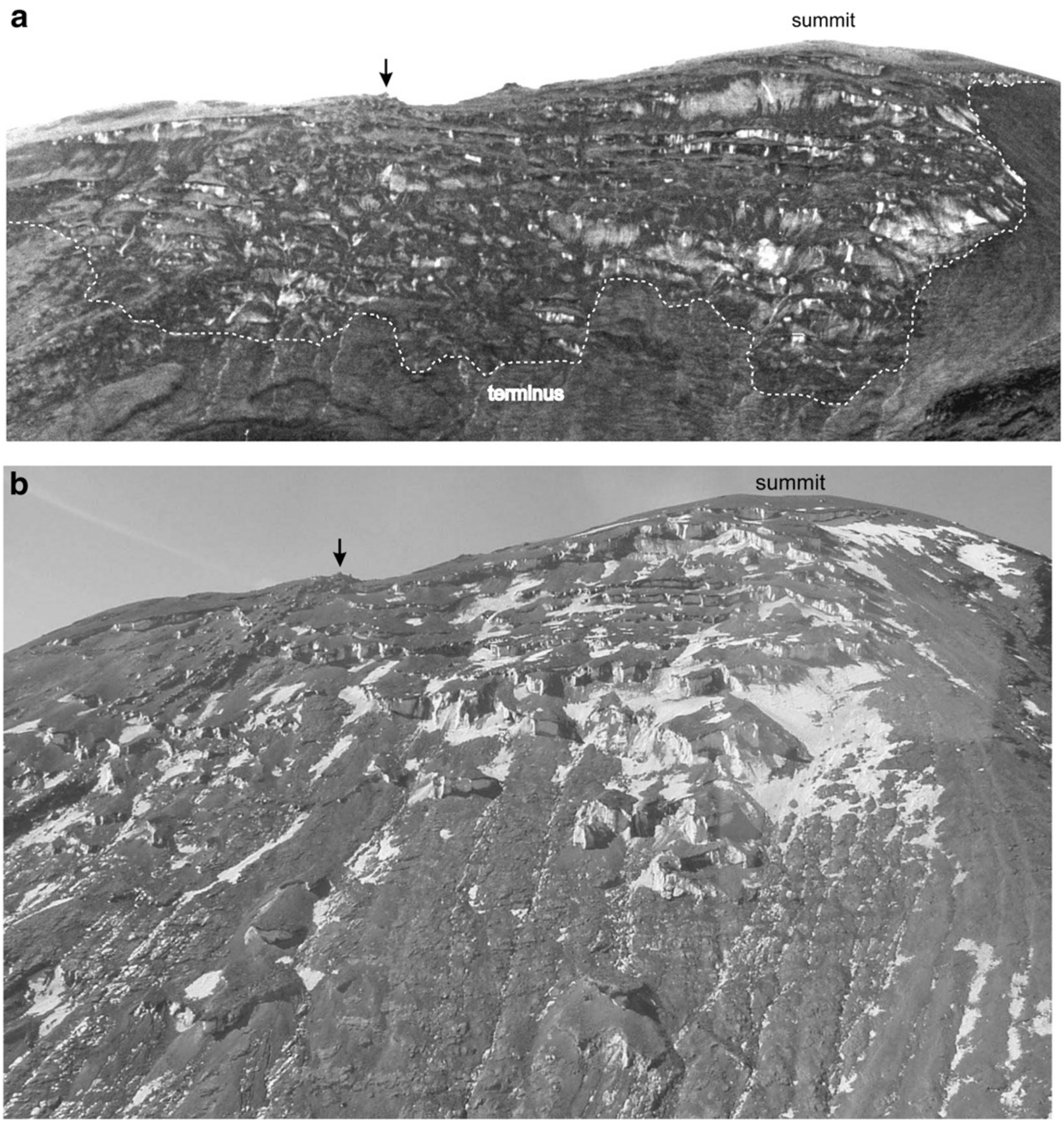

Fig. 9. The glacier at Popocatépetl Volcano. 9a. The glacier was partially covered by tephra, the white portions correspond to walls or ramps of ice. The dashed line shows the glacier boundary. The photograph taken by Lucio Cardenas on 2000. 9b. Close up of glacier remnant, several ice blocks could be distinguish. Photograph taken by Isaac Farraz-Montes on April 20, 2004. To comparison the black arrow indicate the same place.

Fig. 10. Ice block preserved due to insulating effect of the tephra layer at Popocatépetl Volcano. The bar shows an approximate scale. Photograph taken by Hugo Delgado-Granados on November 2005.

explosive phases the glacier was totally covered by tephra. The thickness of tephra increased with subsequent eruptions. In the beginning, tephra was remobilized, by the wind or sheet wash, but intense explosive phases deposited large volumes of tephra that were removed partially by gravity, and sheetwash, or covered by snow falls or hailstorms during summer and winter. After the numerous explosions during December 2000, the glacier volume increased, but in this particular case, the glacier growth was a result of tephra accumulation (Table 3). Tephra on glacier surface affected surface ablation rates, because thin layers enhanced the ablation and thicker layers insulated the underlying ice deterring the ablation, as previously documented for example by Driedger (1981), Mattson et al. (1992), and Nakawo and Young (1981).

The distribution of tephra on the glacial surface was irregular (Fig. 8a). The thickness and distribution were determinate by surface morphology, eruption intensity, and wind direction, among other variables. The glacial surfaces at Popocatépetl were irregular, especially during the periods of maximum ablation (Fig. 8b), when the crevasses enlarged and the surface showed continuous irregularities (i.e., typical conical sublimation structures with heights up to 4 m called "penitents" were formed). This enhanced the irregular distribution of tephra. In low-lying areas the tephra was thick and, at places with steep slopes, such as the tongues, deposition was less. The heterogeneous thickness of debris on the glacial surface provoked differences in the thermal reflectance and insulation properties of the glacier over short distances resulting in dramatic differential ablation effects. In this way, some areas experienced high losses while others were well insulated (see Benn and Evans, 1998). The upper margin of the glacier was repeatedly covered by a large amount of tephra. As a consequence, this part of the glacier remained well insulated and formed almost a flat area delimited by a crevasse, which developed a scarp over the time. The rest of glacier area developed a stair-like morphology (Fig. 9a).

6.4. Tephra remobilization

Manville et al., (2000) established that, once the tephra is deposited on glacial surfaces remobilization processes soon start. For instance, the tephra/snow/water interactions were produced at Ruapehu over a range of scales and controlled by tephra thickness, grain size, distribution and stratigraphy; slope angle, aspect, and nature of the substrate; and climatic parameters such as mean temperature, diurnal temperature range, insulation and precipitation. The remobilization and reworking of tephra were produced by combined processes of diurnal freeze–thaw, surface tension accretion, creep, generation of miniature mudflows, eolian remobilization, sheetwash and rilling.

Similar processes may have occurred at Popocatépetl, but they could not be directly observed because fieldwork was not feasible most of the time due to the risk from the ongoing volcanic activity. Aerial photographs and close-up images of the glacier-covered area (taken with a camera of the CENAPRED monitoring system), allow the observation of processes such as flow generation, sheet wash and rilling. Intense tephra remobilization over glacial surface occurred during the ablation periods due to melting of glacier surface. The melt water induced tephra saturation and subsequent flow generation, sheet wash and rilling. Flow generation and rilling incised the glacier surface over time.

7. Glacial evolution

Based on results and observations, the following four-phase model of glacial evolution at Popocatépetl is proposed.

7.1. Adjustment phase

During 1994–1997, there was no important loss of the glacier-covered area or volume in spite of the intense activity

(Table 1). Notwithstanding, thickening of the glacier front occurred in March 1997. Two zones of maximum thickness can be distinguished on the glacier, one at the terminus and other in the eastern part (Fig. 5a). A feasible explanation is related to the generation of kinematic waves on glaciers.

The velocity of a glacier over large timescales is influenced by changes in the driving forces or shear stress. The stress is controlled by the thickness and surface slope of the ice. High snowfall over the glacial area would thicken the glacier and increase the surface gradient, creating a high stress, which in turn results in increased ice velocity due to sliding as well as internal deformation. Probably, this causes the glacier to discharge excess mass towards the ablation zone. The increase of mass in the accumulation area is transmitted down the glacier in waves of increased velocity known as kinematic waves. Individual packets of ice traveling down-glacier accelerate and decelerate as the wave passes. Kinematic waves are difficult to distinguish at a, non-surging glacier. Nonetheless, such bulges of increased thickness were detectible because they were sufficiently large and traveled down the glacier faster than the ice itself. Kinematic waves have been reported in some glaciers according with Benn and Evans (1998).

The 1966–68 eruptions of Mt. Redoubt (Alaska) reduced the flux of lower part of the Drift Glacier by more than 50%. The flux between the upper and lower parts of the glacier was eliminated for 8 years afterwards, before the glacier was re-connected. The re-connection produced a kinematic wave of thickening which propagated throughout the glacier. After the passage of the kinematic wave, the glacier returned to its pre-eruption equilibrium condition (Sturm et al., 1986).

Eruptive activity during May 1996–March 1997 at Popocatépetl produced uplift of the frontal part of the glacier, but not glacier advance was observed. The tephra deposited on the glacial surface added mass to the glacier, increasing its thickness and surface slope and, as a consequence, its the shear stress and then strain rate. Then, the glacier transmitted mass towards the end of the glacier producing a kinematic wave. The uplift observed in the 1996 orthophoto (Fig. 4) corresponds to the end of the kinematic-wave transmission.

7.2. Thinning phase

Through 1999, the glacier underwent a considerable thinning. The glacier lost ice mass at high rates (Table 3) because of differential ablation related to the irregular distribution of pyroclastic material deposited on its surface during 1997–1998. Also, the kinematic wave transmitted ice to the terminus of the glacier, where the ablation was more intense. By 2000, the thinning continued but was less because of the reduced eruptive activity since 1999. The glacier terminus disappeared and an irregular glacial surface developed lobes with stair-like pattern formed by differential ablation, crevassing and ice flow. The slurry flows and surface rilling related to tephra remobilization by melt water repeatedly incised the glacier surface. Differential ablation and tephra remobilization acted together over time to shape the surface and the mass balance of the glaciers on Popocatépetl.

7.3. Areal retreat phase

In the year 2000, an important areal retreat occurred because of the previous thinning which finally resulted in area loss. The glacial front disappeared. At the same time, the fragmentation of the glacier started to become evident, elongated ice blocks at the upper part of the glacier were generated. The ice blocks at the top were covered by a thick tephra layer and formed a scarp at the front.

7.4. Fragmentation phase

Glacier fragmentation was produced by the combination of differential ablation and recurrence of tephra remobilization processes. By 2001, the glacier was completely fragmented (Fig. 9a), and was reduced to a set of ice blocks (Fig. 9b). The longest ice blocks split the upper part from the rest of the glacier and formed a long escarpment at its front. The scarp was easily identified due to the white color of the ice in comparison with the dark color of tephra layer that covered the glacier. The upper portion of these ice blocks were covered by a thick layer of tephra. The front and sides of the ice blocks exposed the remnant ice to the ablation processes. The eruptive activity or daily insolation induced melting on the walls of ice blocks. The melt water produced was enough to generate flows or sheetwash on the top of the lower ice blocks, as seen in the ortophoto of the year 2001 (Fig 4). Gravitational reworking of tephra due to collapse at the top of the scarps occurred. The tephra was deposited at the base forming small debris fans. Isolated ice blocks located at lower elevations underwent accelerated melting due to daily isolation, mainly during the spring season (Fig. 10).

8. Conclusions

Complex interactions took place between the eruptive activity and the glacier at Popocatépetl Volcano. The glacier evolution and its subsequent extinction was induced by years of fluctuating eruptions. The volcanic processes accelerated and enhanced the loss of glacial volume. The ice accumulation was minimal, resulting in a negative glacier mass balance for the final years (1999–2001). The global climatic factor and the regional climatic influence of Mexico City appeared to be acting prior to the initiation of the 1994 eruption (Delgado-Granados, 1997). Pre-eruptive glacial changes previously documented (Delgado-Granados, 1997) suggest that the eruptive activity was not the single factor, but played a fundamental role in accelerating the demise of Popocatépetl glaciers in 2001.

The study of glacier-volcano interactions during eruptive activity is a complex and challenging task due to numerous factors involved, their interrelations, the timescales and additionally by the fieldwork associated with the study of glaciers on active volcanoes.

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