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Glacier melting and lahar formation during January 22, 2001 eruption, Popocatépetl volcano (Mexico)

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with 6 figures and 2 tables

Summary. During an explosive event that occurred on January 22, 2001, at Popocatépetl volcano, small pyroclastic flows melted part of the glacier and generated a lahar. To evaluate the volume removed from the glacier, before and after the event, digital terrain models were compared. Total removed mass was $\sim 1.0 \times 10^6$ m^3, but a part of it was incorporated in the $\sim 4 \times 10^5$ m^3 lahar as meltwater ($\sim 1.6 \times 10^5$ m^3). The $\sim 2.4 \times 10^5$ m^3 deposit included more than 50% of pumiceous material. An important issue for hazard assessment at ice-clad volcanoes is that not all meltwater plays a role in laharic events.

Résumé. Pendant un événement explosif au volcan Popocatépetl le 22 janvier 2001, des écoulements pyroclastiques de volume modeste ont fondu une partie du glacier et ont engendré un lahar. Pour évaluer le volume du glacier perdu, des modèles numériques de terrain avant et après l'événement ont été comparés. Le volume de glace disparue était de $\sim 1.0 \times 10^6$ m^3, alors que une partie de ce volume ($\sim 1.6 \times 10^5$ m^3) a été retenu comme eau de fonte dans le lahar de $\sim 4 \times 10^5$ m^3. Le dépôt de $\sim 2.4 \times 10^5$ m^3 contenait pleus de 50% de ponces. Un élément important pour qui doit évaluer les risques sur les volcans couverts de glace est le fait que toute l'eau de fusion des glaciers ne participe pas à la genèse des lahars.

1 *Introduction*

Popocatépetl is a large stratovolcano (5452 a.s.l.) comprising an accumulation of lavas, alternating with pyroclastic deposits of andesitic to dacitic composition. Laharic processes have also been present on the volcano even during episodes of quiescence (Fig. 1). The volcano started to erupt on December 21, 1994, and has not yet ended. The eruption has consisted of an alternation of vulcanian explosions with dacitic lava extrusions (Delgado et al. 2001).

During the last decade, the presence of a body of ice at the summit of the volcano has represented a hazard due to possible laharic events caused by ice-melting during eruptive events (Delgado & Brugman 1996). The endangered population of $\sim$8,000 inhabitants lives in towns and villages on the northeastern flank of the volcano and, in particular, in those places located in the vicinity of the glacier-related drainage system. Santiago Xalitzintla (2,327 inhabitants) is a village situated 14 km from the crater, at the outlet of the main drainage from the glacier area. Since the beginning of the eruption several laharic events have occurred (Palacios et al. 1998). Most of them have reached less than 4 km from the source (Delgado et al. 2000), and some of which are suspected to have been generated by eruptive activity-glacier interaction. Major lahar events were registered in June 1997 and January 2001. Both traveled as far as 14 km from the summit, reached the outskirts of Santiago Xalitzintla Village.

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This study describes the role of ice melt in the January 2001 eruptive event by studying the ice-body size and the magnitude of the laharic event. This type of study seeks to evaluate hazards that might occur on other ice-clad volcanoes in Mexico and elsewhere.

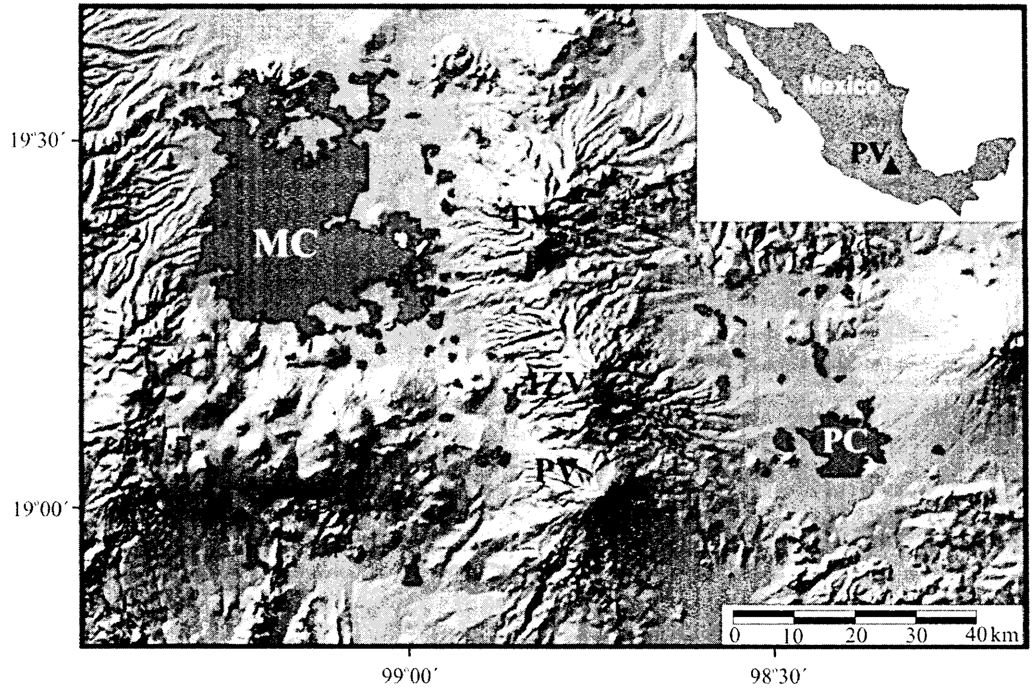

Fig. 1. Location map. Popocatépetl (5,452 a.s.l) is an ice-clad volcano located 70 km southeast of downtown Mexico City and 40 km west of the city of Puebla. It represents the southern end of a north-south volcanic chain known as Sierra Nevada. TV: Telapón volcano; IZV: Iztaccíhuatl volcano; PV: Popocatépetl volcano; MC: Mexico City; PC: Puebla City.

2 *Methodology*

2.1 *Glacier evaluation*

One way to determine the amount of water present on the volcano before and after an eruption is by calculation of the volume of ice. Julio-Miranda & Delgado-Granados (2003) have tackled this issue by applying digital photogrammetry to produce digital terrain models (DTM) and orthophotos, as tools to determine precisely the amount of mass gained and/or lost over a time interval. We have used the ®OrthoEngine software to process aerial photographs taken two days before the explosive event of January 22, 2001 (scale 1:11000), and a month after on February 22, 2001 (scale 1:13000). After digital photogrammetric restitution, DTMs were obtained and the contours of the ice-bodies were digitized. Volumes of ice were extracted by subtracting DTMs using ®Surfer software.

2 *Lahar estimate*

The January 22, 2001, explosion generated several small-size lahars that reached different distances from the source, on the northern and northwestern flanks. The lahars travelled along the gorges: Tlamacas; Tenenepanco; La Espinera and Tetepeloncocone.

These are located on the northeastern flank of Popocatépetl (Fig. 2). Outcrops located in the Tenenepanco (O1) and Huiloac (O2 and O3) gorges were studied, and selected samples from those deposits were analyzed. At the outcrops, three sections (I, II and III) were constructed at proximal, middle and distal locations from the source. These sections were used to estimate the area and volume of the laharic deposits.

The laharic volume was calculated by measuring the lahar travel distance along each gorge and considering the cross sectional area at each outcrop (IVERSON et al. 1998). Grain size analyses were carried out by dry sieve analysis. Results for the smaller laharic deposits are not shown.

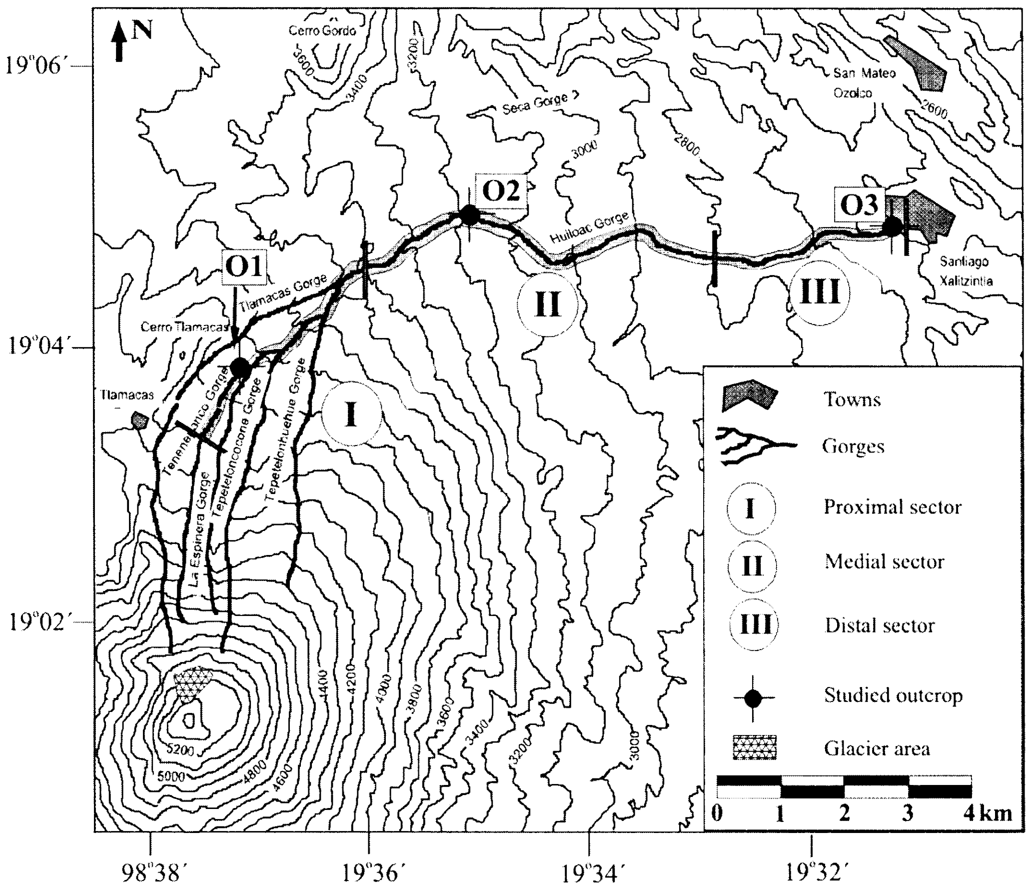

Fig. 2. Map of Popocatépetl's northeastern flank. Location of the lahar deposit outcrops (O1, O2, O3) studied and sectors (I, II, III) in Tenenepanco and Huiloac Gorges.

3 *Ice bodies and eruptive activity*

Two glaciers existed on the northern flank of Popocatépetl (Ventorrillo and Noroccidental), together with small permafrost fields. Before December 1994, glaciers were inactive and showed a retreat trend caused by regional and global climate change (DELGADO 1997). By 1996 40% of the 1958 glacier area disappeared, while 1996–1999 period 22% of the glacier area was lost (HUGGEL & DELGADO 2000). After the eruption started, glacier retreat was accelerated by several processes: temporal and local heat flow increase at glacier bed; pyroclastic material accumulation on glacier's surface; ejection of incandescent material and pyroclastic flow generation, were among the main causes. (DELGADO et al., submitted). The glaciers thinned and shrank. Differential ablation due to heterogeneous distribution of the tephra induced reduction of the glacier, leaving elongated blocks of ice covered by tephra and with frontal ice cliffs (Fig. 3).

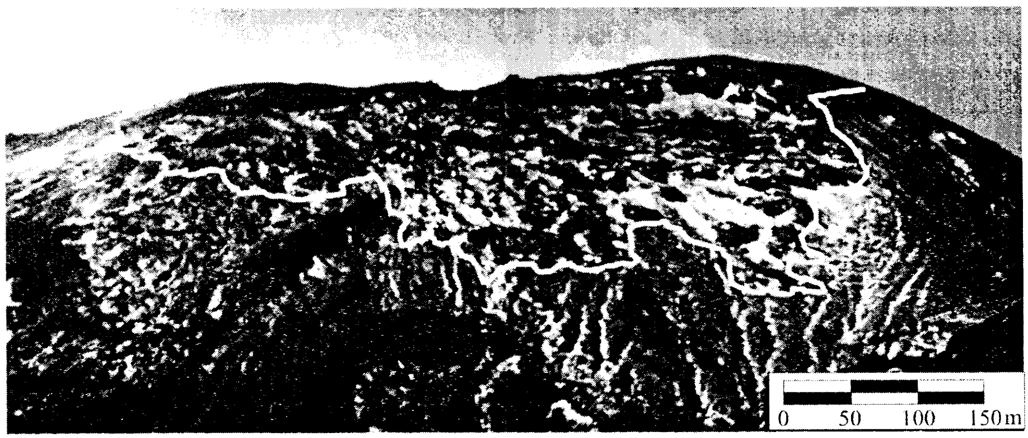

Fig. 3. Photograph of the northern flank of Popocatépetl on February 22, 2003. The white line indicates the area covered by the ice blocks; the dark color is due to a pyroclastic layer on top of the blocks.

A dome-destruction phase starting on December 11, 2000 is of particular interest. During this explosive phase several high eruptive columns were generated and incandescent material was ejected as far as 1 km from the summit. Ashes and blocks were deposited on the glacier's surface. By December 16 the glacier was completely covered by tephra. The explosive activity continued until early January 2001.

On January 22, 2001, at 15:15 (local time), a degassing event began and emission of ash was observed an hour later. At 16:23, the emission of gases and ash continued and incandescent fragments were ejected out the crater. Pyroclastic flows were emplaced on the northern flank, reached 6.5 km from the crater (ROMÁN-CASTILLO et al. 2003). A flow moved down over the glacierized area triggering a lahar. At 20:45, an army brigade, located 5 km from the volcano, reported "a mud flood in the Huiloac Gorge" (CENAPRED reports).

4 *Results*

4.1 *Glacier changes*

Table 1 shows differences in surface areal determinations using DTMs constructed for dates before and after the January 22 2001 event. The areal loss reflects the retreat pattern observed in previous studies (Delgado 1997, Huggel & Delgado 2000, Julio-Miranda & Delgado-Granados 2003). DTM subtraction allowed us to estimate a lost volume of 1 109 804 m^3 (± 11%), equivalent to nearly 1.0 x 10^6 m^3 of water.

Table 1. Area lost at glaciers on Popocatépetl volcano.

Date	Surface area (m^2)	Lost surface area (m^2)
01/20/2001	280357	
02/21/2001	252262	28095

4.2 *Lahar characteristics*

The January 22, 2001, laharic event was associated with the explosive activity and generated presumably by a pyroclastic flow that flowed over glacier's area. The lahar had the characteristics of a debris flow as shown by the deposits studied at three different locations (Fig. 2).

At the proximal zone (Section I), gravel size clasts are the main component at the river bed and border, but sand increases as the main component in the central part of the river bed (Fig. 4, section I). The histograms (Fig. 5) mostly show bimodal distributions, the principal modes are -5ϕ to 3ϕ and a mean grain size between -1.77ϕ and 1.19ϕ. The largest clast size is 1.10 m. The deposit exhibits very poor sorting, which are a characteristic of laharic deposits. The skewness of the deposit reflects fine asymmetry at the border of the river bed and high coarse asymmetry in the center of the river bed. Platikurtic values indicate the broad size distribution of the sediments (Fig. 6).

In the middle zone (Section II) gravel size clasts are the main component at the centre and margins of the river bed (Fig. 4), the sand is the main component in the central channel of the river bed and in the lobate zone. A bimodal distribution (Fig. 5); shows main modes varying from -5ϕ to 3ϕ, and a mean size between -2.77ϕ and 3ϕ. Field observations show that the largest clast size was 40 cm. Values show poor sorting (Fig. 6). The skewness of the middle zone does not establish a clear trend. Platikurtic values reflect the broad size distribution of sediment (Fig. 6).

In the distal zone (Section III) gravel size clasts form the principal component, but in the centre of the channel sand is the main component (Fig. 4). The histograms indicate a bimodal distribution (Fig. 5), at the proximal and middle zones, but in the small central channel of the river the distribution is unimodal. The principal modes vary from -2ϕ to 4ϕ. The mean grain size values are in a range of 0.2ϕ – 3.43ϕ. A maximum size of 2 cm was observed in the field. The sorting varies from very poor to poor. The skewness reflects fine asymmetry in the deposit and a high coarse asymmetry in the small central channel. The platikurtic values show a broad size distribu-

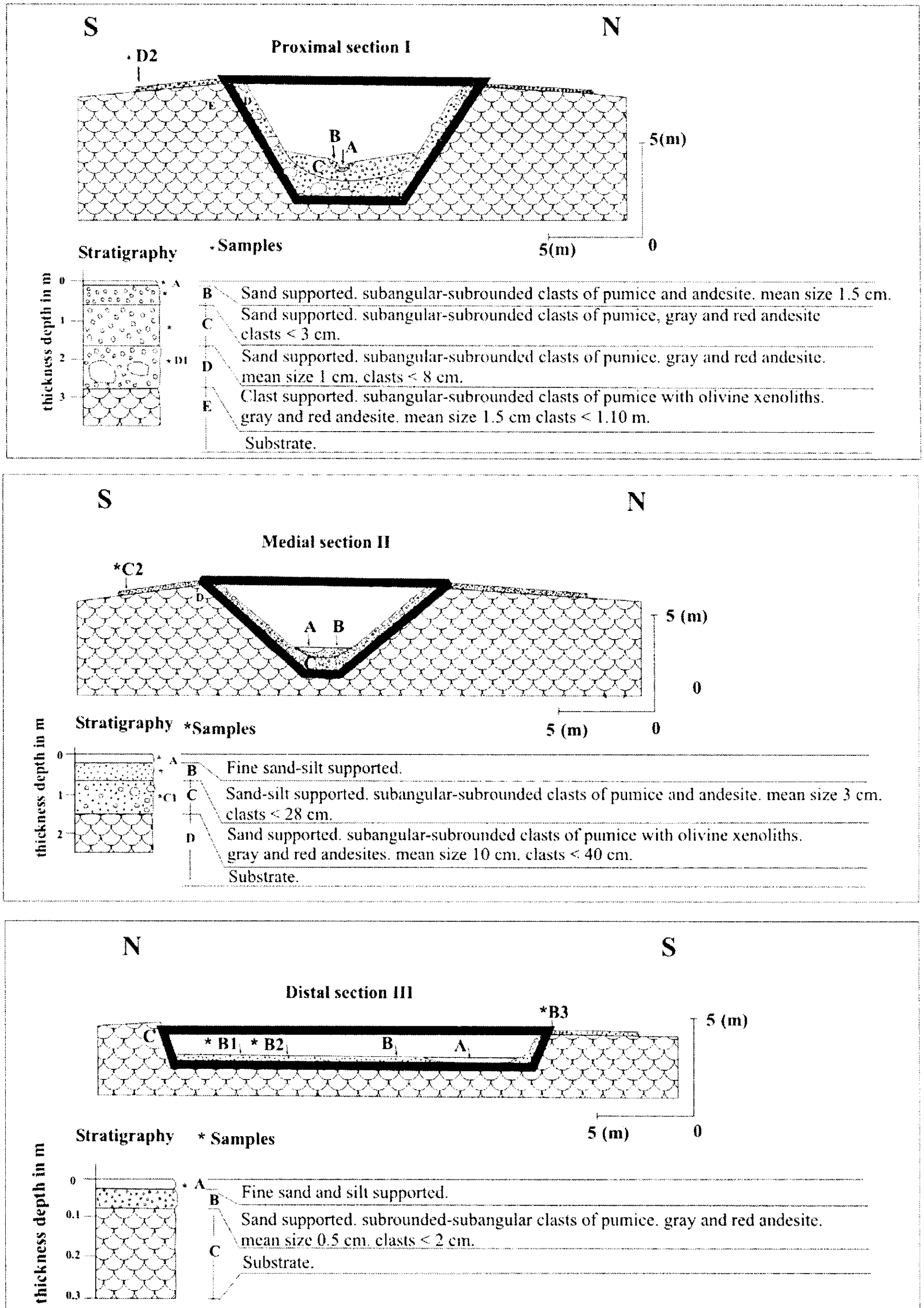

Fig 4. Sections studied on the northeastern flank of Popocatépetl volcano, at 5.5 km, 10 km and 17 km from the vent area. The stratigraphy of the outcrops is described in detail per unit. See location map in Fig. 2.

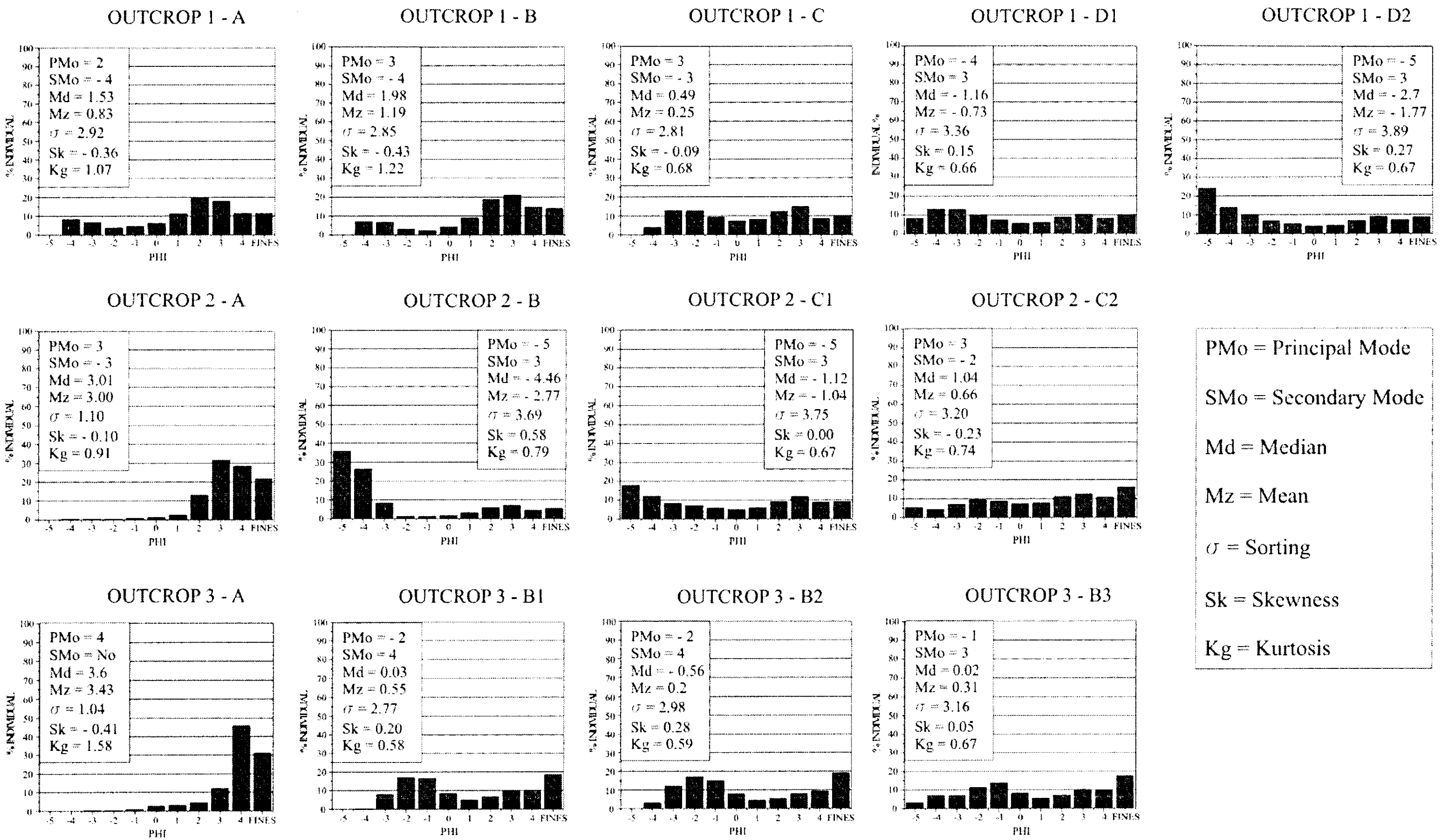

Fig 5. Histograms and statistical parameters calculated following FOLK & WARD (1957) of the samples obtained at every outcrop of the sections, every histogram corresponds to a different unit as named in the section and the stratigraphic column. a. Section I & outcrop I, b. Section II & outcrop 2 and c. Section III & outcrop 3.

tion of the deposit and a leptokurtic value in the small central channel of the river bed, reflect a restricted distribution (Fig. 6).

The sections indicated in Fig. 4 were used to obtain the volume of the laharic deposit of January 22, 2001, according to the parameters shown in Fig. 5. Considering an average sediment content of nearly 60% in debris flow volume, we obtained a volume of sediment of $\sim$ 2.4 x 10^5 m^3 (Table 2). The main components of the flow deposit are pumice, gray and red andesite. Among all these components, pumice represents more than 50% of the total volume as both clasts and matrix. This fact supports the idea that most of the material participating in the laharic event corresponded to a pumice-rich pyroclastic flow that triggered melting of the ice and transported them together as a debris flow. Andesite and dacitic clasts were also incorporated in the debris flow.

Table 2. Lahar volume estimate. The lengths (Fig. 2) were multiplied by the corresponding sectional area (Fig. 4) to obtain the laharic volume of every sector.

Sector	Distance (m)	Section area (m^2)	Lahar volume (m^3)
I	3571	59.21	211439
II	5710	34.54	197223
III	2860	0.34	972
Total	12141	94.09	409634

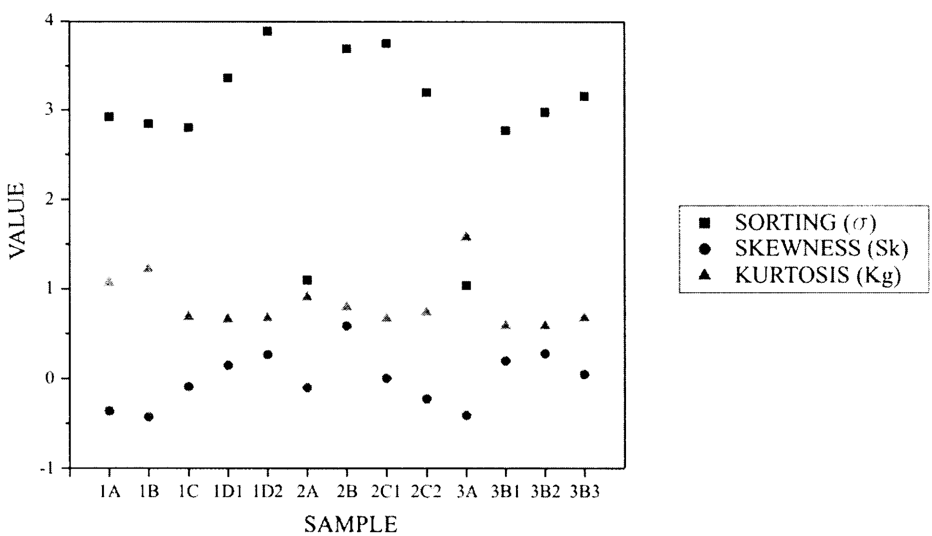

Fig. 6. Sorting, skewness, and kurtosis values for every sample. Explanation in the text.

5 *Discussion*

Description and characterization of the laharic event of January 22, 2001, and resulting deposit were important for identification of the role of the glacier's meltwater and the interactions between the glacier and volcanic activity. Clast size, sorting, skewness and kurtosis indicate that the studied laharic deposits are debris flow related. The contents of the deposit indicate that more than 50% of the clasts are made of pumice as a consequence of the pumiceous pyroclastic flows.

The estimated laharic volume in this study differs from those of other authors. CAPRA et al. (2003) estimated a flow volume of 2.3×10^5 m^3. In this study a laharic volume of 4×10^5 m^3 is reported. The differences in volume are explained in terms of the delineation of proximal zone of the deposit. A day after January 22nd eruptive event an important deposit was recognized upstream of the Huiloac Gorge in the feeding Tenenepanco Gorge. This was considered the proximal area in this study, whereas CAPRA et al. (2003) considered the proximal area to be in the Huiloac Gorge.

The total volume of meltwater released during eruptions does not fully participate in the generation of lahars. During the November 13, 1985, eruption of Nevado del Ruïz (Colombia) the meltwater released was estimated in 43×10^6 m^3 (THOURET 1990), but nearly 50% of that water did not contribute to lahar generation. The water was incorporated to snow avalanches, sediment-laden avalanches, phreatic explosions, sublimation generated by pyroclastic flows or it was stored in the glacier. Similar processes, including percolation, might have occurred at Popocatépetl volcano where total mass removed ($\sim 1.0 \times 10^6$ m^3) was larger than the water in the lahar ($\sim 1.6 \times 10^5$ m^3).

Calculated removed mass include melted ice and tephra. During the volcanic activity that took place since December 11 2000, was accumulated on the glacier's surface. The early January DTM represents a surface modified by deposition of volcanic materials. The February DTM shows a landscape transformed by the removal of both volcanic debris and ice.

The mass difference among DTMs as compared to the volume of the laharic deposit and particularly to the sediment (less than 1.2×10^5 m^3 of tephra) and water ($\sim 1.6 \times 10^5$ m^3) allow us to establish that $\sim 8.1 \times 10^5$ m^3 of ice were removed from the glacier but did not participate in the laharic event. The resulting melting water was sublimated by the pumiceous pyroclastic flow or percolated.

6 *Conclusions*

The subtraction of DTMs allowed the calculation of the total mass removed from the glaciated slopes of Popocatépetl volcano ($\sim 1.0 \times 10^6$ m^3) by the explosive event of January 22, 2001. The meltwater and pumice from the collapsing explosive column, together with volcanic materials accumulated on the glacier in December 2000, participated in a lahar (a debris flow) that traveled along the northern gorges of the volcano. The laharic event left behind a deposit of $\sim 2.4 \times 10^5$ m^3, consisting of more than 50% of pumiceous material, and $\sim 1.6 \times 10^5$ m^3 of meltwater (1.7×10^5 m^3 of removed ice) was incorporated in the lahar. This represents $\sim 17\%$ of the total ice mass removed.

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References

CAPRA, L., POBLETE, M.A. & ALVARADO, R. (2004): The 1997 and 2001 lahars of Popocatépetl volcano (Central Mexico): textural and sedimentological constraints on their origin and hazards. – J. Volcanol. Geotherm. Res. **131:** 351–369.

CENAPRED (Centro Nacional de Prevención de Desastres): Reports of Popocatépetl's eruptive activity. – Available from: www.cenapred.unam.mx

DELGADO, H. (1997): The Glaciers of Popocatépetl Volcano (Mexico): changes and causes. – Quatern. Internat. **43:** 1–8.

DELGADO, H. & BRUGMAN, M. (1996): Monitoreo de los glaciares del Popocatépetl. – In: UNAM & CENAPRED (eds.): Volcán Popocatépetl. Estudios realizados durante la crisis de 1994–1995. – Secretaría de Gobernación: 221–244.

DELGADO, H., CÁRDENAS-GONZÁLEZ, L. & PIEDAD-SÁNCHEZ, N. (2001): Sulfur dioxide emissions from Popocatépetl volcano (Mexico): case study of a high-emission rate, passively degassing erupting volcano. – J. Volcanol. Geotherm. Res. **108:** 107–120.

DELGADO, H., GONZÁLEZ-HUESCA, L.A.E. & OROPEZA-VILLALOBOS, B. (2000): Possible linkage between laharic events and glacier ice melting at Popocatépetl volcano, Mexico. – In: GULICK, V.C. & GUDMUNSSONN, M. (eds.): Volcano/Ice Interaction on Earth and Mars. – Abstracts, August 13–15, 2000, p. 10; Reykjavík, Iceland.

DELGADO-GRANADOS, H., HUGGEL, C., JULIO-MIRANDA, P., CÁRDENAS-GONZÁLEZ, L., ORTEGA DEL VALLE, S. & ALATORRE-IBARGÜENGOITIA. M.A.: Chronicle of a death foretold: extinction of the small-size tropical glaciers of Popocatépetl volcano (Mexico) – Geology (Submitted).

HUGGEL, C. & DELGADO, H. (2000): Glacier monitoring at Popocatépetl volcano, Mexico: glacier shrinkage and possible causes. – In: HEGG, C. & VONDER MUEHLL, D. (eds.): Beiträge zur Geomorphologie. – Proceedings der Fachtagung der Schweizerischen Geomorphologischen Gesellschaft vom 8.–10. Juli 1999 in Bramois (Kt. Wallis), pp. 97–106; Birmensdorf, Eidgenöss. Forschungsanstalt WSL.

IVERSON, R.M., SCHILLING, S.P. & VALANCE, J.W. (1998): Objective delimitation of lahar-inundation hazards zones. – GSA Bull. **110** (8): 972–984.

JULIO-MIRANDA, P. & DELGADO-GRANADOS, H. (2003): Fast hazard evaluation, employing digital photogrammetry: Popocatépetl glaciers, Mexico. – Geofís. Internac. **42** (2): 275–283.

ROMÁN-CASTILLO, J., MACÍAS-VÁZQUEZ, J. & ARCE-SALDAÑA, J.L. (1990): El flujo piroclástico Tenenepanco, ocurrido el 22 de enero de 2001 en el volcán Popocatépetl. – IV Reunión Nacional de Ciencias de la Tierra, Resúmenes, 31 Octubre–5 Noviembre, 2003, p. 221; México.

THOURET, J.C. (1990): Effects of the November 13, 1985 eruption on the snow pack and ice cap of Nevado del Ruiz volcano, Colombia. – J. Volcanol. Geotherm. Res. **41:** 117–201.

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