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Study of Ayoloco Glacier at Iztaccíhuatl volcano (Mexico): hazards related to volcanic activity – ice cover interactions

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with 4 figures and 2 tables

Summary. Iztaccíhuatl (5286 masl) is an active volcano in central Mexico capped by several ice bodies. We carried out a series of glaciological and volcanological studies in order to assess hazards associated with eruptive products interacting with ice. Measurement of the areal extent of Ayoloco glacier for 1982 and 1998, allows retreating patterns to be recognised. The likely causes of this retreat are global and regional warming, although volcanic forcing is not ruled out due to the presence of a diffuse-degassing field nearby. A ground penetrating study allowed us to calculate the volumes of Ayoloco glacier ice in 1998. Using these volumes we estimated possible volumes for lahars that might be generated during a future eruptive activity.

Résumé. Le volcan Iztaccíhuatl (5286 msnm), volcan actif du Mexique central, est couvert de plusieurs glaciers. Nous avons réalisé une série d'études glaciologiques et volcaniques, afin de pouvoir évaluer le risque d'un probable interaction entre les produits éruptifs et la glace. Les mesures de surface du glacier Ayoloco réalisées entre 1982 et 1998 montrent une réduction de l'extension glacée due probablement a un réchauffement global et local sans pour autant écarter les forces volcaniques dues a la proximité d'une dégasification diffuse. Des études profondes du terrain réalisées en 1998 ont permis de calculer le volume du glacier Ayoloco. Prenant en considération ce volume, nous avons estimé le volume probable des lahars qui pourraient se produire pendant une éventuelle éruption volcanique.

1 *Introduction*

Iztaccíhuatl volcano (*White Woman* in the náhuatl language, also known as the *Sleeping Woman*), is the third highest mountain in the country (5286 masl), is located 45 km southeast of Mexico City (Fig. 1) and is one of the ice-capped volcanoes of Mexico, together with Citlaltépetl and Popocatépetl (Lorenzo 1964). Even though Iztaccíhuatl has been considered for a long time to be extinct volcano (Mooser 1958), recent reports on diffuse degassing and seismic events at the volcano and its vicinity indicate that this is, in fact, an active, yet dormant volcano (Delgado 2001).

Volcanic activity-ice interaction is a very important issue that should be studied at any ice-clad volcano. The consequences of this interaction might be catastrophic, as was shown during the debris-flow event of November 1985 at Armero (Colombia) where a relatively moderate eruptive event of Nevado del Ruíz volcano made evident the need to study interaction at active volcanoes (Pierson et al. 1990, Thouret 1990).

Categorization of Iztaccíhuatl as an active volcano and the presence of glaciers at its summit make it an important target for the study of related hazards. Most glaciers in the world are retreating

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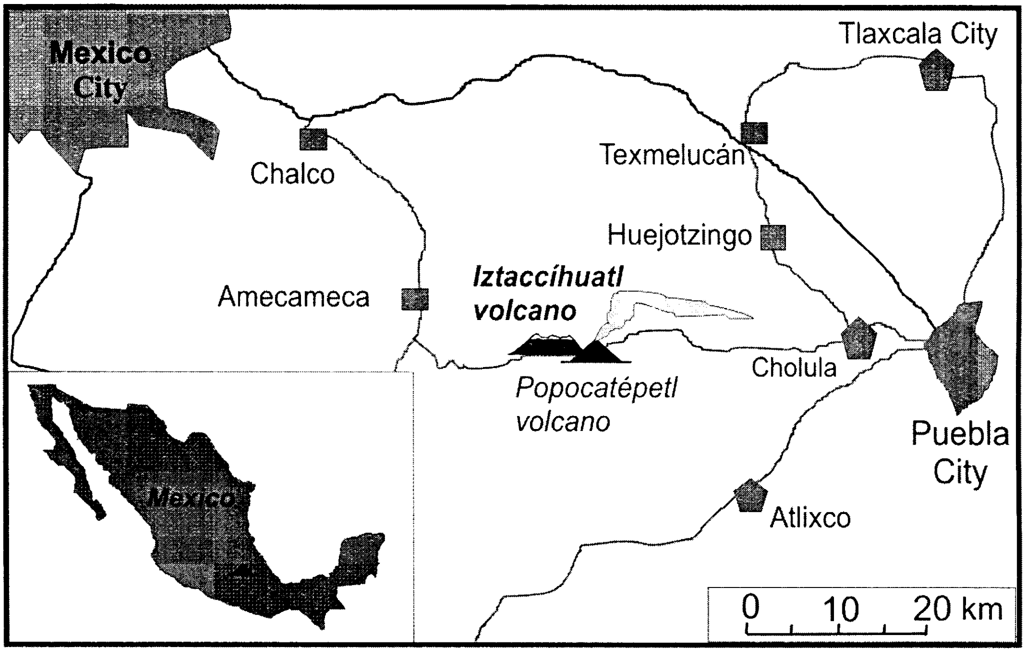

Fig. 1. Location map. Iztaccíhuatl volcano and vicinity.

(HAEBERLI et al. 2002), however the retreat at active volcanoes might not only be caused by climatic forcing, but also by volcanic-related causes (DELGADO 1996/1997). Therefore, it is important to study these tropical glaciers in order to discriminate the likely influence of increasing volcanic activity from climatic effects. These studies should include mapping of specific glacierized areas and periodic observations of them. Results should yield conclusions on the evaluation of associated hazards. This work reports a study of Ayoloco glacier of Iztaccíhuatl volcano (Fig. 2). Glaciological and volcanological observations are considered in order to produce a first attempt at evaluating volcano-related hazards.

2 *Previous studies*

Important advances in the study of intertropical glaciers have been made though the matter has not been fully researched (KASER & OSMASTON 2001) in spite of evidences for retreat of small intertropical glaciers (RAMÍREZ et al. 2001, DELGADO 1996/1997).

In Mexico, the efforts have been directed to the study of the impact of eruptive activity on the glaciers of Popocatépetl volcano and the hazards inherent to the melting of glacier ice (DELGADO & BRUGMAN 1995, PALACIOS et al. 1998, HUGGEL & DELGADO 2000, JULIO MIRANDA & DELGADO 2003, JULIO MIRANDA et al. 2005).

Even though the first reference to the glaciers of Iztaccíhuatl volcano was made in 1781–1789 (ALZATE 1831), their formal study and measurement were firstly tackled by LORENZO

(1964). For the first time, this author measured the size of the glaciers of Iztaccíhuatl volcano by using aerial photographs which were re-stituted photogrammetrically. Twelve glaciers were described and measured and Lorenzo reported a total glacierized area of 1,164,550 m^2, out of which Ayoloco glacier had an area of 247,500 m^2. The equilibrium line was at 4895 m. a.s.l. (White 1981). This study was continued in 1984–1985 (Delgado & Arciniega 1985, Delgado et al. 1985). This time, three glaciers were considered extinct, and the rest were described and classified. Finally, Álvarez & Delgado (2002) applied ground penetrating radar (GPR) techniques to study the morphology of the ice at depth and investigate the buried volcanic landforms.

3 *Glacier measurements*

3.1 *GPS survey*

We carried out a GPS survey of selected locations in order to obtain a precise positioning of GPR start and endpoint surveys for accurate profile length calculation and elevation difference corrections.

This GPS survey in fast-static mode was done with Trimble 4000 SSe receivers and geodetic L1/L2 antennas recording at 5sec sampling frequency. A reference site at Cerro Altzomoni was also established. The Altzomoni site was processed using ambiguity resolution and a solution into ITRF97 (International Terrestrial Reference Frame), while glacier sites were processed using a double difference method and referred to the Altzomoni permanent station UTM coordinates (536365 m, 2114136 m, 4029 m).

3.2 *Glacierized areas*

We determined the area of Ayoloco glacier by using a 1:20,000 scale orthophoto map with contour lines every 20 m produced by the Mexican Mapping Agency (INEGI 1982). This orthophoto allowed the extraction of a digital elevation model (DEM). On the DEM, the boundaries of the glacier were digitized (Fig. 2), and its area was obtained. Using a series of photographs obtained during fieldwork, the boundaries of the glacier in 1998 were also digitized in order to estimate the glacierized area for 1998 (with ±30 m uncertainty). Ice temperatures were obtained by installing thermometers (suitable for maximum-minimum record) at various depths into ice holes drilled with a hot-point driller to a maximum depth of 6 metres.

3.3 *GPR profiling*

In order better to estimate ice body volumes, a ground penetrating radar (GPR) profile was carried out following a transect with minor elevation differences (Fig. 2).

Profiling of glaciers has been one of the most successful applications of the GPR. This is due to the low electromagnetic losses in ice, as well as to the signal contrast among low-density material ($\sim$0.9 g/cm^3), compared with volcanic rocks (commonly 2.5–3.1 g/cm^3). For this reason, GPR profiling was chosen for the task of determining glacier thickness using an Ekko IV radar system.

Fig. 2. DEM of Iztaccíhuatl volcano showing the extent of Ayoloco glacier in 1982 and 1998 (dashed and solid line, respectively). The GPR profile location is indicated with a black line, and the dotted area is the diffuse-degassing field.

A radar profile, 415 m in length with orientation of 190° in azimuth, was carried out using 100 Mhz antennas in the reflection mode, with a separation of 2.5 m and a step size of 2.5 m; signal-recording time was from 0 to 900 ns. No crevasses were intersected along the profile line.

A common mid-point (CMP) survey was performed containing 12 stations, with a separation of 0.5 m, to determine wave velocity propagation in the glacier's ice. Results yielded a value of 0.17 m/ns, which is close to the reported value for ice of 0.16 m/ns (e.g., ARCONE et al. 1998). The antennas were in close contact with the ice cover. Fig. 3a shows the radargram obtained along the profile. Saturation correction, first break point correction, and first break shift were applied. The average trace has been subtracted from all the records in order to enhance dipping layers. A constant gain of 5.0 was applied and an interpolated section was constructed. Data have been suppressed at various intervals, since the radar response contained spurious signals at those locations, and replaced with interpolated values, yielding a more continuous radargram.

Fig. 3b shows the GPR interpretation. The profile may be described in general as a layered medium with thin surface layering (0.3–0.5 m), and thicker layering (1.5–2.0 m) underneath, which is perturbed by faulting. A earlier interpretation (ÁLVAREZ & DELGADO 2002), placed emphasis on the identification of the thinner layering in the glacier. Herein (Figs. 3a and 3b) the major trends of interphases and faulting are highlighted, confirming the hypothesis that the GPR line cut across one of the several volcanic craters at the summit. The dominant faulting pattern inside the crater dips from south to north at the bedrock (Fig. 3b, lower right). Besides fissures and crevasses, faults also exist in the glacier ice and start near to the surface, cut the layers, and die out at depths of 30 to 50 m. Some of them are listric faults. This region behaves as brittle ice and the deepest crevasses have deep roots. At the southern tip of the profile, beneath the bottom of the glacier, a series of layered structures are also observed, these are probably layers of volcanic material.

The lower part (below 50 m deep) is thought to be related to the presence of ductile ice since fractures are absent. A transitional region from the brittle to the ductile ice is inferred under locations 60 to 230 m and at 50m depth. Projection of the glacier-bedrock interface, marked as C, suggests a depth of approximately 85 m at location 150 m when the ice propagation is taken as 0.17 m/ns. Interphase I is interpreted as tephra cemented by ice, altered rock or a combination of both. This interpretation is based on observations made at the northern and southern ends of the profiles where tephra and altered rocks were seen.

Since the survey line was bounded by rock outcrops at both ends, the crater's length must be close to the size of the line (i.e., ~500 m). This geometry allows for a preliminary estimate of the volume of the ice body of the Ayoloco glacier.

4 *Ayoloco glacier*

La Panza is the source zone of Ayoloco glacier (at ~5100 masl) and two other glaciers: Centro Oriental (Central-eastern); and Sur Oriental (South-eastern). The western edge of La Panza is the beginning of a steep slope where Ayoloco glacier discharges towards the Milpulco valley ending at an altitude of 4890 masl (Fig. 2). At the place where the steep slope begins, a crevasse field is present. At this field séracs are sometimes produced, being another way for the glacier to lose mass.

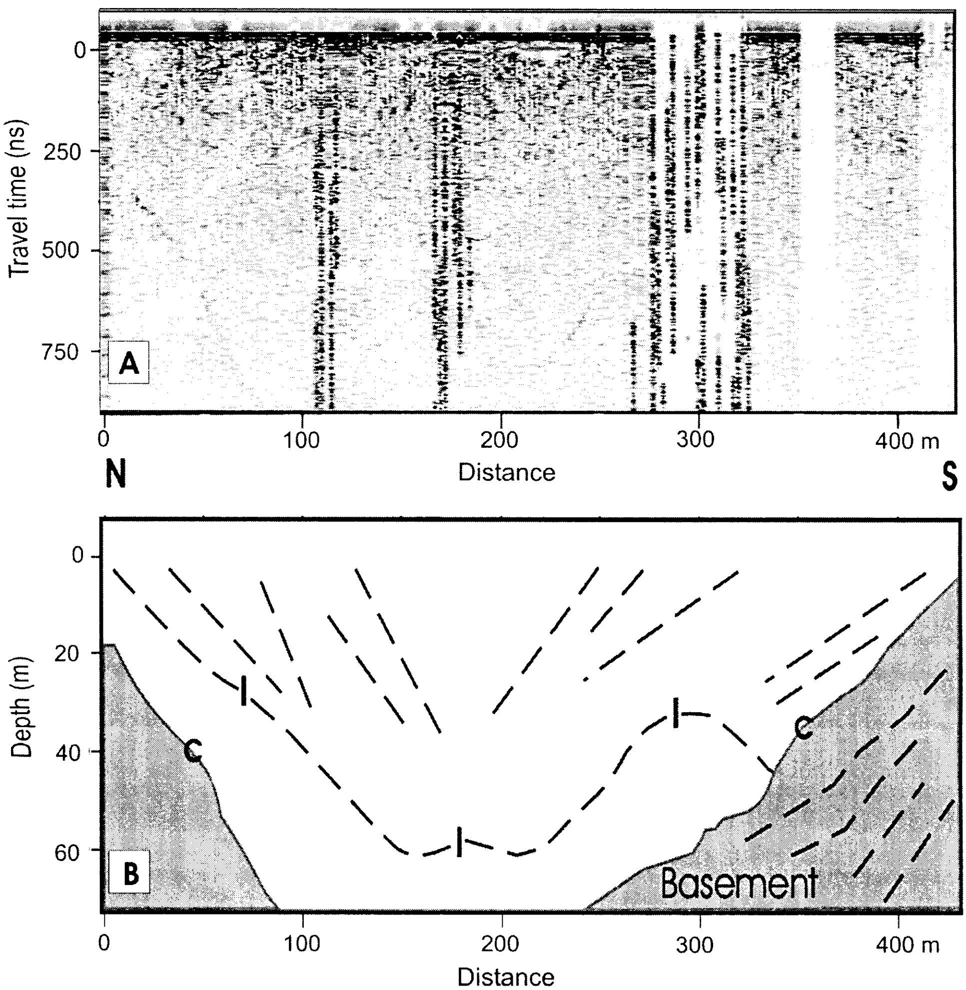

Fig. 3. GPR profile for upper Ayoloco glacier. (A) radargram. (B) interpretation.

La Panza is a flat plateau where snow accumulation takes place due to its morphology (Fig. 4). Most of the snow melts extensively during the dry season (January–May) due to intense radiation at this altitude. Part of the snow on the surface sublimates, resulting in ice conical shapes (*penitents*) and water ponds at their base. The resulting water progressively refreezes during the night and is, thus, converted into glacier ice. Such glacier ice has no internal structure, and is rather a glass-type glacier ice. The average temperature of the glacier ice is ~-1.5°C (ranging from -2.0°C to 0.5°C) and therefore, the existence of englacial water bodies (described as water pockets by Álvarez & Delgado 2002) is likely inside the uppermost part of the glacier. This is implied by the GPR profile. The average density of glacier ice was measured at ~910 kg/m^3.

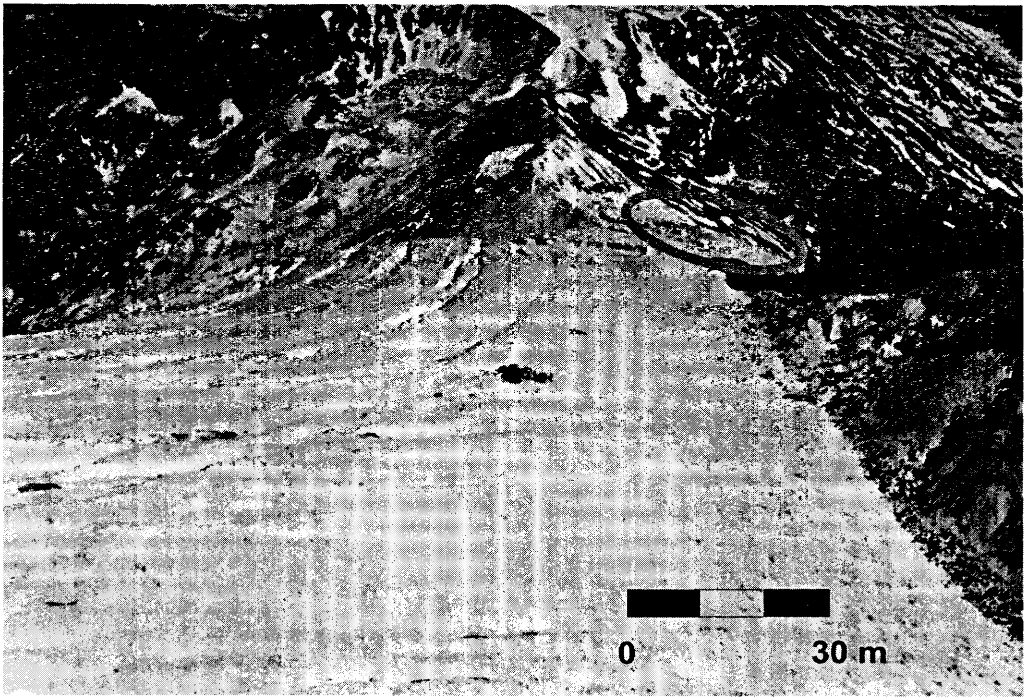

Fig. 4. La Panza is an almost flat region where three glaciers meet. The diffuse-degassing field is indicated. View from the south.

An area of 251000 m^2 was obtained preliminarily for 1982 by combining the use of topographic maps and ASTER imagery (ÁLVAREZ & DELGADO 2002). We reported in this study an area of 218340 m^2 for 1982 by using an orthophoto as described above. Also, an area of 140890 m^2 is reported for 1998 (<10% error for both). In this case, the use of the DEM allowed us to estimate the areas of the upper and lower Ayoloco glacier. The area of the upper Ayoloco glacier is estimated in 84930 m^2 while the area of the lower part is 55960 m^2.

The maximum thickness could not be detected with our GPR profiling, but is more than 70 m. However, the thickness obtained in the profile indicates the maximum thickness for the upper Ayoloco glacier whose average is ~40 m. In the case of the lower Ayoloco glacier the average thickness is estimated at ~20 m according to direct observations. With these figures, the total volume of the glacier ice at Ayoloco glacier in 1998 was ~4516400 m^3.

Ayoloco glacier has been strongly retreating during the past few decades. In 24 years (1958–1982) the glacier lost 12% from the 1958 total area (Table 1), whereas from 1982 to 1998 it lost 43%. It is worth noticing that retreat is located mainly at the northern and western sides of Ayoloco glacier because these are the parts that are more exposed to heat from the diffuse degassing area and sunlight.

5 *Volcanic activity*

Iztaccíhuatl is an old volcano (NIXON 1989). The construction of the cone started about 0.9 Ma. During the first construction stage (between 0.9–0.6 Ma) Llano Grande and Los Pies volcanoes were formed and at the end of this stage, the latter collapsed towards the southeast (SIEBE et al. 1995). The remains of this collapse may be seen at the town of Atlixco. After 0.6 Ma, during the second constructive stage, the current Iztaccíhuatl volcano was formed in between the two previous structures. Afterwards, two lava domes were formed (El Solitario and Los Yautemes). At about 0.27 Ma, lavas and scoria were emitted from the south (at La Joya), whilst dacitic lavas were extruded at El Téyotl 80000 years ago (NIXON 1989). 5000 years ago, more lava domes were extruded south of Los Pies volcano (SIEBE et al. 1995).

Table 1. Areal retreat of Ayoloco glacier from 1958 to 1998.

Year	Area (m2)	No. of years	Areal difference (m2)	Average retreat rate (m2/year)	% from total	% retreat
1958	247.500					
1982	218.340	24	-29.160	-1.215	88	12
1998	140.890	16	-77.450	-4.841	57	43

Iztaccíhuatl volcano has been showing signs of activity whilst dormant. The evidences of its activity are: the occurrence of earthquakes and degassing. Volcano tectonic earthquakes have been observed during the last few years at the edifice surroundings by the National Seismological Service at the University of Mexico (UNAM). However, precise location laterally and at depth is difficult due to a lack of a seismic network dedicated to monitor this volcano. The nearby seismic network devoted to Popocatépetl volcano, operated by the National Center for Disaster Prevention and UNAM (PACHECO, pers. comm.), also records some data relevant to the study area. Nevertheless, the most evident sign of volcanic activity at Iztaccíhuatl is degassing. Degassing at Iztaccíhuatl volcano has been recognized for long time by mountaineers because of the presence of a strong 'rotten-eggs' odour at the northern part of La Panza. But it was not until recently when the source of degassing was discovered. This is a relatively wide area where diffuse degassing occurs (Fig. 4), but no fumarolic vent exists.

Centro Oriental glacier once covered this same area; however the glacier has almost disappeared due to the heat flow at the degassing area. The ground temperatures are between 0–10°C (measured with a thermocouple) and any snow cover only lasts very short time.

We located a volatile trap (or alkaline trap) station at this diffuse-degassing field for volcanic gas sampling and collected wind-dispersed volcanic vapours (NOGUCHI & KAMIYA 1963). This method has been successfully applied at several volcanoes (e.g. WILLIAMS et al. 1990, ITALIANO et al. 1991, GOFF et al. 1998), especially when direct volcanic-gas-sampling is not feasible. The alkaline trap sampled volcanic vapours for a month and the bulk concentrations of several anions and cations in the sample were measured. The trap consisted of a plastic beaker (20 cm high, 15 cm wide) containing 4N KOH, put beneath an inverted and ventilated bucket. Ventilation of the bucket allows the gases to contact the caustic solution.

The results of chemical analyses for samples of April–May, 1999 indicate the presence of magmatic components. The presence of NA^+, K^+, Ca^+, Mg^+ and SiO_2 (with concentrations between 0.5 to 4.2 ppm) is ambiguous, and might be related to other processes. However, the presence of F^-, in spite of its low concentration (<0.5 ppm), suggests a magmatic source for the vapours. Furthermore, the presence of sulfur (analyzed as $SO_4^=$) was present at more than 20 ppm. There are several spots on the mountain where the intense odour is felt suggesting their existence. Another pointer to their likely existence is that some volatile species, such as sulfur dioxide, can be detected remotely.

Diffuse degassing can be so intense that SO_2 emissions may be measured by correlation spectrometry. Determination of SO_2 emission rates at Iztaccíhuatl volcano has been made using a *Barringer* correlation spectrometer (COSPEC) model V. The methodologies used for these determinations are described by STOIBER et al. (1983), WILLIAMS-JONES & STIX (in press), or STIX et al. (in press). All measurements made at Iztaccíhuatl volcano were airborne, using fixed-wing twin-engine planes, making three traverses beneath and perpendicular to the gas plume. Volcanic plume direction and velocity were assumed to be the same as the wind determined using air navigational GPS. Distances from the summit of the volcano to the closest point of the traverse were about 10 km.

Even though the emissions may not be compared with those of its southern neighbour, Popocatépetl volcano, the emissions are in the high range for dormant volcanoes (DELGADO et al. 2001). The results are 130 tons/day in average for a period between 1996 and 2000. Considering the lack of a fumarolic vent for the volcano, these emission rates are high but little is known on emissions from diffusively degassing volcanoes due to a lack of measurements.

The volcano, in summary, shows signs of activity and, though dormant, these indications should be taken into account for the evaluation of hazards related with its likely eruptive activity.

6 *Potential future volcano and glacier interactions*

In the previous sections we have described the size of Ayoloco glacier. Also, we have shown evidence of the activity of Iztaccíhuatl volcano that indicate that this is a dormant, yet not an extinct, volcano. Furthermore, the GPR profile suggests that Ayoloco glacier is nested within a volcanic crater.

The glacier retreat at Iztaccíhuatl volcano could be the response to global change and the influence of nearby largely polluted areas such as Mexico City and Puebla. However, the four-fold increase in the retreat rate within the last decades (1958–1982 in comparison to 1982–1998) might also be the combined effect of the previous factors, plus a manifestation of slight increase in the signs of volcanic activity.

This evidence, together with the fact that diffuse-degassing occurs within the boundaries of the recognized crater; suggest that future eruptive activity might produce ice melting. If such scenario occurs, then the generation of laharic events is one of the possibilities.

The magnitude of a possible future eruption can not be forecasted at present nor its location, size or date. But, if were the active vent were to be La Panza crater, then melting of Ayoloco glacier ice is a real possibility. We have calculated the equivalent water for the volume of ice present at Ayoloco glacier in 1998 and have used the proportions of water/clasts (40–65%) existing in the literature to calculate the volume of lahars (debris flows and hyper-concentrated flows) that can be generated if the Ayoloco glacier was melted in 5, 25, 50, or 100% by the presumed eruptive activity (PIERSON & SCOTT 1985, PIERSON 1986, JULIO MIRANDA & DELGADO 2003), assuming that all melted water participates in the lahar (Table 2). Noticeably, 50–100% glacier melting has not been witnessed on active volcanoes so far and rarely all melted water from glaciers participates in a lahar, but we show the related to figures for comparison. The magnitude of the 'worst-case-scenario lahars' (almost impossible to occur) resulting from melting of 50–100% Ayoloco glacier ice (not taking into account other glaciers on this volcano), in terms of volume would compare at maximum to the laharic events that occurred in 1980 during the eruption of Mt. St. Helens.

Table 2. Volumes of documented laharic events compared to hypothetical laharic volumes generated by glacier-volcanic activity interaction at Ayoloco glacier at indicated ice-melt percentages. DF: debris flow, HF: hyperconcentrated flow. Data from 1) GONZÁLEZ HUESCA (2000), 2) PIERSON et al. (1990), 3) PIERSON (1986), CUMMANS (1981), 4) GALLINO & PIERSON (1985), and 5) this study.

Volcano/Country	Lahar	Volume (m3)
Popocatépetl, MX (1)	San Nicolás Lahar	70.000.000
Nevado del Ruíz, CO (2)	Río Azufrado	55.000.000
Mt. St. Helens, USA (3)	S. Fork Toutle R.'80	13.000.000
Mt. Hood, USA (4)	Mt. Hood 1980	76.000
Iztaccíhuatl, MX (5)	Ayoloco 100% DF	10.161.900
Iztaccíhuatl, MX (5)	Ayoloco 100% HF	6.253.477
Iztaccíhuatl, MX (5)	Ayoloco 50% DF	5.080.950
Iztaccíhuatl, MX (5)	Ayoloco 50% HF	3.126.738
Iztaccíhuatl, MX (5)	Ayoloco 25% DF	2.540.475
Iztaccíhuatl, MX (5)	Ayoloco 25% HF	1.563.369
Iztaccíhuatl, MX (5)	Ayoloco 5% DF	508.095
Iztaccíhuatl, MX (5)	Ayoloco 5% HF	312.674

The probability of the 5–25% scenarios, however, is higher and could also be produced by strong non-volcanic melting, or sudden release of subglacial water. An issue not specifically analyzed in this study relates to the stability of Ayoloco glacier. Increasing heat flux at the base of the glacier by volcanic activity and/or increasing temperatures due to atmospheric warming may make this steeply inclined glacier (35–70°) prone to failure which could result in major ice/rock avalanches.

7 *Conclusions*

Iztaccíhuatl volcano is a dormant volcano showing signs of activity. The disastrous consequence of the interaction between potential eruptive activity and the presence of glaciers is an important motivation to carry out research in the volcano-glacier environment.

Iztaccíhuatl volcano has several glaciers on its upper region, Ayoloco glacier among them. This glacier is nested in an old crater that shows diffuse degassing. Thus, we attempted a hazard evaluation of likely laharic flows produced by melting of glacier ice during hypothetical eruptive activity.

This 140890 m^2 glacier has an average thickness of $\sim$40 m at the upper part and $\sim$20 m in the lower part. The separation of the two sections of the glacier, assisted by a DEM, allowed the calculation of the total volume of ice ($\sim$4516400 m^3). Considering its equivalent water and scenarios of 5–25% of melting during a potential eruptive event, we obtained laharic volumes up to $\sim$2540000 m^3, that are far smaller from those occurred during the eruption of Mt. St. Helens in 1980 ($\sim$13000000 m^3). Caution is required for this kind of computed ice volumes due to errors that are difficult to evaluate during the calculation process (i.e. errors in orthophoto map construction).

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References

Álvarez, R. & Delgado, H. (2002): Characterization of a tropical ice body on Iztaccíhuatl volcano, Mexico. – In: Koppenjan, S.K. & Lee, H. (eds.): Ninth International Conference on Ground Penetrating Radar. – Proceeding of SPIE **4758:** 438–442.

Alzate, J.A. (1831): Observaciones físicas ejecutadas por Don José Antonio Alzate en la Sierra Nevada. – Gaceta de Literatura **I:** 99–107.

Arcone, S.A., Lawson, D.E., Delaney, A.J., Strasser, J.C. & Strasser, J.D. (1998): Ground-penetrating radar reflection profiling of groundwater and bedrock in an area of discontinuous permafrost. – Geophysics **63:** 1573–1584.

Cummans, J. (1981): Chronology of mudflows in the South Fork and North Fork Toutle River following the May 18 eruption. – In: Lipman, P.W. & Mullineaux, D.R. (eds.): The 1980 eruptions of Mount St. Helens, Washington. – US Geol. Surv. Prof. Paper **1250:** 479–486.

Delgado, H. (1996/1997): The Glaciers of Popocatépetl Volcano (Mexico): changes and causes. – Quatern. Internat. **43/44:** 1–8.

Delgado, H. (2001): Iztaccíhuatl. – In: Delgado, H. (ed.): Los Volcanes de México. – Chapter "Los Silenciosos", pp. 116–119; Dirección General de Publicaciones UNAM.

DELGADO, H. & ARCINIEGA, R. (1985): Los glaciares de México: metodologías para su estudio. – Memorias de la Reunión Anual de la U.G.M. 1985: 194–204.

DELGADO, H. & BRUGMAN, M.M. (1995): Monitoreo de los glaciares del Popocatépetl en Volcán Popocatépetl. – In: CENAPRED (Secretaría de Gobernación)-UNAM: Volcán Popocatépetl, Estudios Realizados Durante la Crisis de 1994–1995. – 221–244.

DELGADO, H., ARCINIEGA, R. & CALVARIO, D. (1985): Los glaciares del Popocatépetl e Iztaccíhuatl. – Memorias de la Reunión Anual de la U.G.M. 1985: 178–193.

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

GALLINO, G.L. & PIERSON, T.C. (1985): Polallie Creek debris flow and subsequent dam-break flood of 1980, East Fork Hood River Basin, Oregon. – U.S. Geol. Surv. Water-Supply Paper **2273:** 22 pp.

GOFF, F., JANIK, C.J., DELGADO, H., WERNER, C., COUNCE, D., STIMAC, J.A., SIEBE, C., LOVE, S.P., WILLIAMS, S.N., FISCHER, T. & JOHNSON, L. (1998): Geochemical surveillance of magmatic volatiles at Popocatépetl volcano, Mexico. – Geol. Soc. Amer. Bull. **110:** 695–710.

GONZÁLEZ HUESCA, A.E. (2000): Estudios de detalle estratigráfico y sedimentológico del lahar de San Nicolás en el flanco noreste del volcán Popocatépetl. – Thesis, 109 pp.; Facultad de Ingeniería UNAM.

HAEBERLI, W., MAISCH, M. & PAUL, F. (2002): Mountain glaciers in global climate – related observation networks. – WMO-Bulletin **51:** 18–25.

HUGGEL, C. & DELGADO, H. (2000): Glacier monitoring at Popocatépetl volcano, México: glacier shrinkage and possible causes. – In: HEGG, CH. & VONDER MÜHLL, D. (eds.): Beitrage zur Geomorphologie. – pp. 97–106; Proceedings der Fachtagung der Schweizerischen Geomorphologischen Gesellschaft vom 8. bis 10. Juli 1999, Bramois. WSL Birmensdorf.

INEGI (Instituto Nacional de Estadística, Geografía e Informática) (1982): Fotomapa del Volcán Iztaccíhuatl, scale 1:20,000.

ITALIANO, F., NUCCIO, P.M., PECORAINO, G. & VALENZA, M. (1991): Monitoring of acid gases at the crater of Vulcano using the method of alkaline traps. – Acta Vulcanol. **1:** 249–254.

JULIO MIRANDA, P. & DELGADO, H. (2003): Fast hazards evaluation employing digital photogrammetry: Popocatépetl glaciers, México. – Geof. Internat. **42:** 275–283.

JULIO MIRANDA, P., GONZÁLEZ HUESCA, A.E., DELGADO, H. & KÄÄB, A. (2005): Glacier melting and lahar formation during January 22, 2001 eruption, Popocatépetl volcano (Mexico). – Z. Geomorph. N.F., Suppl.-Vol. **140:** XXX–XXX.

KASER, G. & OSMASTON, H. (2001): Tropical Glaciers. – 228 pp.; Cambridge University Press.

LORENZO, J.L. (1964): Los Glaciares de México. – Monografías del Instituto de Geofísica, Universidad Nacional Autónoma de México **I:** 123 pp.

MOOSER, F. (1958): Active Volcanoes of Mexico. – In: MEYER, A.H. & MACBIRNEY, A.R. (eds.): Catalogue of Active Volcanoes of the World Including Solfatara Fields. Part VI. Mexico and Central America. – 36 pp.; International Volcanological Association, Naples.

NIXON, A.G. (1989): The geology of Iztaccíhuatl volcano and adjacent areas of the Sierra Nevada and Valley of Mexico. – Geol. Soc. Amer. Spec. Paper **219:** 58 pp.

NOGUCHI, K. & KAMIYA, H. (1963): Prediction of eruptions by measuring the chemical composition and amount of gases. – Bull. Volcanol. **24:** 367–378.

PALACIOS, D., ZAMORANO, J.J. & PADILLA, G. (1998): Proglacial debris flows in Popocatépetl north face and their relation to 1995 eruption. – Z. Geomorph. N.F. **42:** 273–295.

PIERSON, T.C. (1986): Flow behavior of channelized debris-flows, Mount St. Helens, Washington. – In: ABRAHAMS, A.D. (ed.): Hillslope Processes. – pp. 269–296; Allen and Unwin, Boston.

PIERSON, T.C. & SCOTT, K.M. (1985): Downstream dilution of a lahar:transition from debris flow to hyperconcentrated stream flow. – Water Resourc. Res. **21:** 1511–1529.

PIERSON, T.C., JANDA, R.J., THOURET, J.-C. & BORRERO, C.A. (1990): Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruíz, Colombia, and consequent mobilization, flow and deposition of lahars. – Journ. Volcanol. Geotherm. Res. **41:** 17–66.

RAMÍREZ, E., FRANCOU, B., RIBSTEIN, P., DESCLOITRES, M., GUÉRIN, R., MENDOZA, J., GALLAIRE, R., POUYAUD, B. & JORDAN, E. (2001): Small glaciers disappearing in the tropical Andes: a case-study in Bolivia: Glaciar Chacaltaya (16°S). – Journ. Glaciol. **47:** 187–194.

SIEBE, C., ABRAMS, M. & MACÍAS, J.L. (1995): Derrumbes gigantes, depósitos de avalancha de escombros y edad del actual cono del volcán Popocatépetl. – In: CENAPRED (Secretaría de Gobernación)-UNAM: Volcán Popocatépetl, Estudios Realizados Durante la Crisis de 1994–1995. – 195–220.

STIX, J., WILLIAMS-JONES, G. & HICKSON, C. (in press): Applying the COSPEC at Active Volcanoes. – In: HICKSON, C. & STIX, J. (Eds.): The COSPEC Cookbook. – Geolog. Surv. Canada.

STOIBER, R.E., MALINCONICO Jr., L.L. & WILLIAMS, S.N. (1983): Use of the Correlation Spectrometer at Volcanoes. – In: TAZIEFF, H. & SABROUX J.C. (eds.): Forecasting Volcanic Events. – Developm. Volcanol.: 425–444; Elsevier Science Publisher, The Netherlands.

THOURET, J.-C. (1990): Effects of the November 13, 1985 eruption on the snow pack and ice cap of Nevado del Ruíz volcano, Colombia. – Journ. Volcanol. Geotherm. Res. **41:** 177–201.

WHITE, S.E. (1981): Equilibrium line altitudes of late Pleistocene and recent glaciers in central Mexico. – Geogr. Ann. **63A:** 241–249.

WILLIAMS, S.N., STURCHIO, N.C., CALVACHE, M.L., MÉNDEZ, R., LONDONO, A. & GARCÍA, N. (1990): Sulfur dioxide from Nevado del Ruiz volcano, Colombia: Total flux and isotopic constraints on its origin. – Journ. Volcanol. Geotherm. Res. **42:** 53–68.

WILLIAMS-JONES, G. & STIX, J. (in press): Using the COSPEC in the Field. – In: HICKSON C. & STIX, J. (Eds.): The COSPEC Cookbook. – Geol. Surv. Canada.

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