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Fast hazard evaluation employing digital photogrammetry: Popocatépetl glaciers, Mexico

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RESUMEN

La generación de flujos laháricos originados por la fusión de nieve y hielo es uno de los principales peligros asociados a erupciones en volcanes cubiertos por glaciares. En estos casos, la evaluación de los peligros asociados debe realizarse de manera rápida y segura, por lo que se hace necesario el empleo de la percepción remota. La fotogrametría digital es una rama de la percepción remota que permite el estudio de la interacción glaciares/actividad volcánica mediante el empleo de software especializado, orientado al tratamiento de imágenes a partir de fotografías aéreas, con lo cual se obtiene en poco tiempo información confiable, que posibilita el monitoreo de la evolución de los procesos y en consecuencia la evaluación de peligros.

Antes de la actual actividad eruptiva, los glaciares del Popocatépetl fueron estudiados con métodos directos, pero después de 1994 el trabajo de campo se tornó riesgoso, por lo que fue necesario implementar un método basado en la percepción remota que permitiera continuar con el estudio de los cambios que se presentan en estos glaciares. En este trabajo se discute la aplicación de la fotogrametría digital a la evaluación de peligros mediante su aplicación a un problema específico: la medición de las áreas glaciales del Popocatépetl para diciembre del 2000 con el objeto de estimar el volumen equivalente de agua, así como plantear diversos escenarios de fusión glacial y los volúmenes laháricos correspondientes. Este trabajo muestra que incluso una fusión del 100% de hielo no generaría un evento lahárico de magnitud comparable con el lahar San Nicolás, o del evento del Nevado del Ruíz.

PALABRAS CLAVE: Volcán Popocatépetl, glaciares, fotogrametría digital, evaluación de peligros, monitoreo glacial.

ABSTRACT

Lahar floods are among the main hazards originated by ice and snow melting during eruptions of glacier-clad volcanoes. Hazard evaluation can be fast and safe by using remote methods such as digital photogrammetry, using software for image processing of scanned aerial photographs. Digital photogrammetry also allows monitoring of the evolution of geological processes.

Before the onset of the current eruptive activity, Popocatépetl glaciers were studied by direct methods. After December 1994, it became necessary, for safety reasons, to find a remote method to continue with the study of glacier changes. In this paper, a hazard evaluation methodology is discussed and applied to measurement of glacier areas at Popocatépetl on December 2000 with the aim to determine equivalent water volume and to estimate maximum and minimum laharic volumes for different ice-melting scenarios. Our results show that even a 100% ice melting would not produce a laharic event of the size of the catastrophic lahars at Nevado del Ruíz or San Nicolás.

KEY WORDS: Popocatépetl volcano, digital photogrammetry, glaciers, hazard evaluation, glacier monitoring.

INTRODUCTION

Volcanic activity produces morphological changes occurring within specific places and time scales. Lava flow movement and emplacement, dome growth, ground deformation or glaciers/volcanic activity interaction produce morphological modifications on volcanoes or over nearby areas in short periods of time. These processes can evolve rapidly, endangering people and infrastructure. Fast evaluation of changes is needed for hazard assessment.

Studies of morphodynamic processes associated with volcanic activity require the use of new methodologies for obtaining reliable data to be used in evaluation and forecasting of associated hazards. For instance, during dome-growth episodes at large stratovolcanoes, a knowledge of the effusion rate is needed in order to anticipate a change in eruptive style. A change from effusive activity alone to effusive activity accompanied with pyroclastic flows phase may mean different hazards and require a different response.

The study of glacier/volcanic activity processes is very important for hazard assessment. Lahar generation is the principal hazard originated by snow and ice melting during volcanic eruptions in the presence of ice bodies. Debris flows and hyperconcentrated flows occurring at volcanoes are collectively referred to as lahars (Smith and Fritz, 1989). Major and Newhall (1989) studied 108 historical eruptions where snow and ice were involved. They concluded that 60% of the laharic flows were produced by lava flows increasing the heat flow at the base of glaciers, by ejection of hot water from a crater lake or by tephra fall; the other 40% were produced by pyroclastic flows, surges, heat blasts or rock avalanches. Among volcanic phenomena, lahars have caused a large number of deaths (Blong, 1984). The volume and range of the lahars depend on the available water and thus, for hazard assessment at glacier-clad volcanoes the volume of ice should be known. Also, during simulations of laharic events it is important to estimate the amount of water in the form of ice or snow in order to estimate possible volumes of laharic flows and identify the likely affected area (Delgado and Brugman, 1996). Available volcanic sediments is another important parameter for laharic volume assessment for events occurred in the past, although this may not allow a close estimate as in the case of ice volume determination.

On the other hand, morphological changes in a glacier may be premonitory of changes in volcanic activity. Unusual crevasse patterns, ice deformation or thickness changes may indicate an increase of basal heat flow or deformation of the volcano under the glaciated area (Brugman and Meier, 1981). Ideally, timely detection of changes to evaluate processes occurring beneath the glacier could help forecast glacier collapse and prevent a laharic event.

Ice volumes may be estimated in a number of ways, including remote sensing and geodetic methods. The choice of the study method at volcanoes depends on the eruptive behavior and thus, on the risk level. If the risk is high, fieldwork is not feasible and remote sensing is the only safe tool. At high-altitude mountains photogrammetry has been employed for recognition of hazards such as glacier floods, ice avalanches, glacier length variations, creeping and thawing frozen debris, and rock slope instability (Haeberli *et al.*, 1989; Kääb *et al.*, 1997; and Kääb, 2000), and also for glaciological studies (Østrem and Brugman, 1991; Paterson, 1994; Kääb *et al.*, 1999). On volcanoes, photogrammetry has been used for glacier monitoring during eruptions aiming for early recognition of hazards related to bulging and glacier shrinkage (Moore and Albee, 1980; Huggel and Delgado, 2000).

In Mexico, three large stratovolcanoes are ice-capped: Citlaltépetl or Pico de Orizaba (5700 m.a.s.l), Popocatépetl (5452 m.a.s.l.) and Iztaccíhuatl (5282 m.a.s.l). Popocatépetl is currently under eruption since 1994. The glaciers of Popocatépetl volcano are the best-known Mexican glaciers (Lorenzo, 1964; Delgado *et al.*, 1986; Delgado, 1993; Delgado and Brugman,1996; Delgado, 1997, Palacios,1995; Palacios *et al.*, 1998 and Huggel and Delgado, 2000). However, since the onset of the eruption, fieldwork has turned highly risky.

Before the onset of the current eruption (December, 1994) Popocatépetl´s glaciers showed a shrinking trend. The causes were claimed to be global and regional climatic factors (Delgado, 1993). However, during the current eruptive activity most glacier changes are attributable to volcanic activity (Huggel and Delgado, 2000).

Since eruptive activity began, glacier studies at Popocatépetl volcano became more relevant under two perspectives: glaciological and volcanological. The first, because of the strong influence of eruptive activity on the extent of glaciers and regime, i.e. retreat, glacier surging. The second, because possible melting and collapse of the glacier may trigger laharic events of a wide range of magnitudes depending on the ice mass involved. During the current volcanic activity several lahars have been generated. The most important occurred on July 1, 1997, reaching the village of Santiago Xalitzintla 13 km from the source on the northeast slope. On January 22, 2001 an explosive event generated a more than 20 km high column and small pyroclastic flows interacted with the glacier. This interaction provoked a laharic flow that reached the vicinity of Santiago Xalitzintla again.

Study of interaction between eruptive activity at the volcano and glaciers is of great importance for laharic hazards assessment. Part of these studies is the measurement of the ice volume body and related changes.

Early studies of Popocatépetl glaciers were done by direct methods, but after 1994 the risk associated to fieldwork increased, and a methodological change was needed. Indirect or remote sensing methods for measuring glacier changes were sought in order to avoid exposure of researchers’ life.

This paper deals with the implementation and application of image processing techniques for glacier area measurements. The objective is to estimate glacier areas for 16 December 2000 airphotos from Popocatépetl volcano by using digital photogrammetry, in order to figure out related hazards due to sudden ice melting.

POPOCATÉPETL VOLCANO AND ITS GLACIERS

Popocatépetl is an active stratovolcano in central Mexico (Figure 1), 60 km southeast of Mexico City, one of the largest cities in the world. There are numerous villages around the volcano. Santiago Xalitzintla is the nearest village, with 33 000 inhabitants, near the outlet of the streams that drain glacier watersheds. Evaluation of laharic hazards related to the interaction between volcanic activity and glaciers is of great local importance.

The first glacial inventory was due to Lorenzo (1964). Later Delgado (1993) and Huggel and Delgado (2000) con-

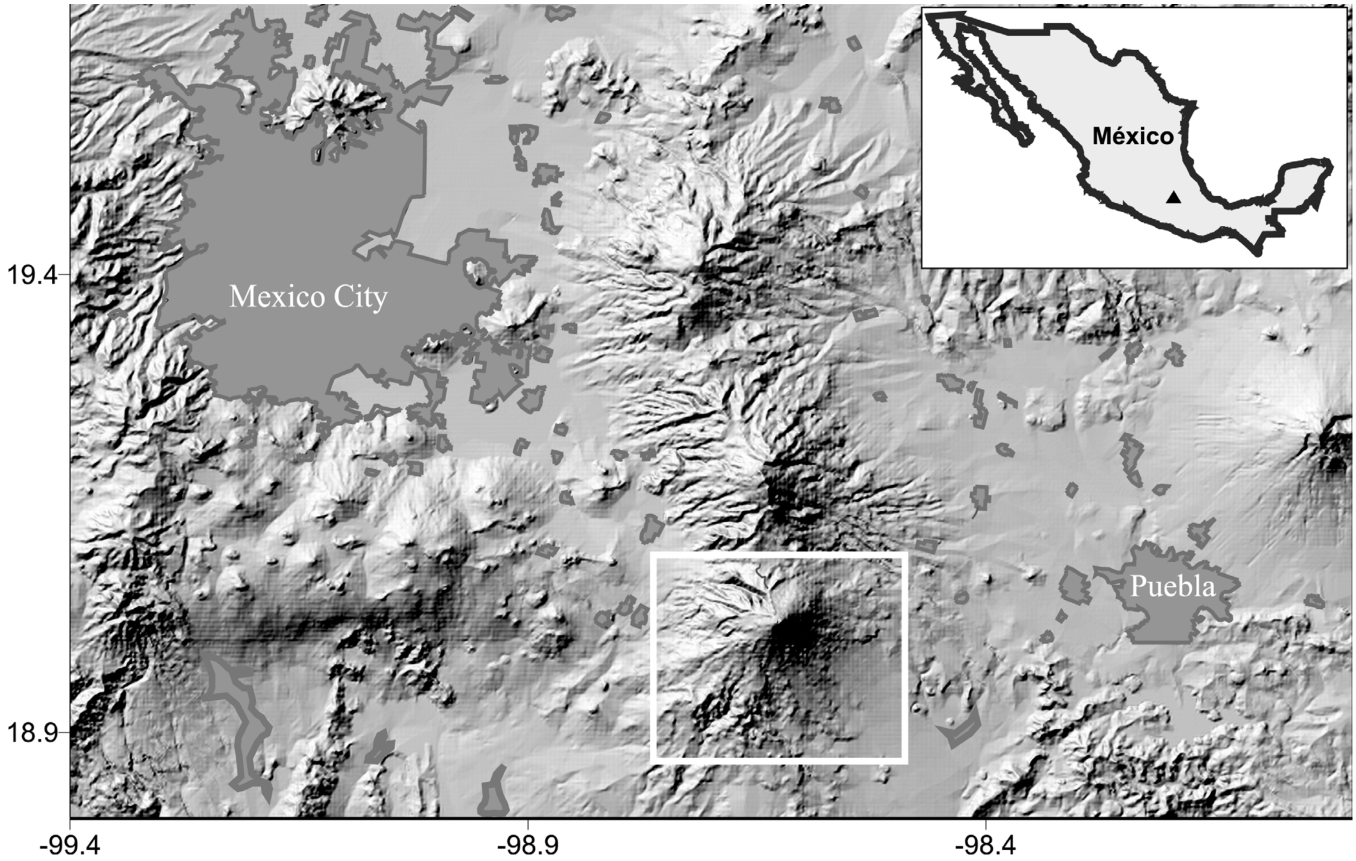

Fig. 1. Location of Popocatépetl volcano (inside of white square), surrounded by several cities and villages.

tinued glacier studies with the aim of quantifying glacier changes in time.

There are two glaciers at Popocatépetl volcano: Glaciar del Ventorrillo and Glaciar Noroccidental. Andesitic lava flows constitute the bedrock although the easternmost part lies on recent volcanic ash and lava flows. Glaciar del Ventorrillo is a simple basin mountain glacier on the northern slope, characterized by a single accumulation area and a multi-lobed tongue. The major source of nourishment is snow and hail. The glacier develops an intricate crevasse system. Glaciar Noroccidental is a glaciarete on the northwest side of the volcano. It is bounded downslope by a steep cliff where the tongue is suddenly interrupted. To the east, the boundary with Glaciar del Ventorrillo is marked by a ridge know as El Ventorrillo. To the west, the glacier dies out on the steep lava slopes. Most of this glacier is black ice. The lack of crevasses in most of the glacier suggests a stationary glacier. It is the remnant of a hanging glacier fed mainly by snow, and shares its accumulation area with Glaciar del Ventorrillo. Both glaciers are considered to be part of the same glacier except for the fact that Glaciar del Ventorrillo drains to the northeast and eventually to the east, toward the State of Puebla (Delgado, 1997).

IMAGE PROCCESING

Digital Orthorectifying Process. Aerial photographs must be geometrically corrected before the photos can be employed for measurements. Lens distortion, earth curvature, refraction, camera tilt and terrain relief must be corrected or minimized (Welch and Jordan, 1996). For small areas the earth curvature correction is not needed. The process of correcting and removing these distortions consists in a) correction of systematic displacements, and b) rectification. This removes geometric distortion of photos and establishes a working scale. As a part of the rectification process, an affine transformation between a reference coordinate map and the digitized aerial photograph is established. The digitized photograph is resampled to create a rectified image. Differential rectification adds a further correction for terrain relief, through the use of a digital elevation model (Welch and Jordan, 1996). The digital orthorectifying process requires the following inputs: aerial photographs, camera-specific parameters, a set of ground control points (GCP), and a digital elevation model (DEM). The following general steps are required (Welch and Jordan, 1996): a) The aerial photograph is scanned and converted to raster image; b) Location of fiducial marks and GCPs on the image; c) Rectification, employing mathematical transformation parameters to establish the relationship between the ground and the image; and d) An additional differential rectification employing terrain height data from a DEM in order to correct relief displacements in the image.

Airphotos. Aerial photographs must be scanned and converted to raster format before they can be used in digital image processing. A decision concerning the scanning process will determine, among other things, the geometric accuracy of the resulting images, the information content and processing speed of the image analysis. During digitization, the reflectivity of the set of instantaneous fields (IFOV) is sampled and quantified.

Two kinds of scanners can be used for digitization depending on the photographs. Aerial photographs may be available sometimes as prints on paper or as film transparencies. Most commercial photographs are sold as paper prints but transparencies are best for digitization. Transparencies result in higher spatial resolution and greater range of gray values as compared with the results from using paper-prints (Welch and Jordan, 1996).

It is necessary to compile some details at the moment of photograph acquisition, such as flight altitude. Scale is given by altitude above ground and focal length, such data usually appear on the data strip. Also, data on camera calibration is needed and can be obtained from the calibration report (camera type, fiducial marks, focal length, calibration date, etc.). This report is supplied by the aerial photograph provider. Scale is important, large scales are more useful to identify glacier changes, especially in small glaciers.

For glacier studies the use of aerial photographs taken during the ablation season is suggested as glaciers are uncovered by seasonal snow, the morphology is clear and the recognition of glaciated areas is relatively easy. Accuracy is much higher when the photographs are made without meteorological or volcanological cloud cover.

Ground Control Points (GCP). A ground control point is a point with coordinates (X, Y, Z) obtained by conventional ground surveys from published maps, aerotriangulation, or by using a Global Position System (GPS). GCPs are required as parameters for the affine transformation. GCPs should be a set of geographical features of known location recognizable on the images.

Digital Elevation Model. A DEM consists of a network of sampled object values in the XY plane with Z-values at every node of the network. A DEM may include rules of interpolation of Z-values at arbitrary XY locations. The network data structure may be a raster, a quad tree, a triangular irregular network (TIN), or any combination of the three. DEM allows the geometrical description of the entire surface of an object by three-dimensional coordinates. DEM data can be obtained by several methods; photogrammetry is among the most common procedures. A DEM is a very important tool for glacier studies. The combination of a DEM with digital image-processing techniques provides a better interpretation of glacial phenomena at inaccessible regions or areas under risk (Rentsch *et al.*, 1990).

Software for Orthorectifying. Commercial software for image processing is available with varying capabilities and costs. Limp (1999) provides a review of this software, considering GIS interoperability, multiple format interoperability, CAD operations, visual display and enhancement, classification methods, geometric rectification, orthophoto generation, radar analysis, classification and processing of hyperspectral data, cost and performance. Packages such as ENVI™, ERDAS IMAGINE®, ER Mapper™, Image Analyst™, PCI and TNTmips™ are described. In relation to photogrammetric capabilities, OrthoEngine Airphoto Edition (OEAE) by PCI Geomatics® is well suited for orthoimage generation from scanned aerial photographs.

OrthoEngine® has several modules which can be selected according to the user preferences. OEAE contains an efficient triangulation method to generate precise orthophotos from scanned or digital camera aerial photographs.

MEASUREMENT OF POPOCATÉPETL GLACIATED AREA

The aerial photographs used in this research were obtained from Secretaría de Comunicaciones y Transportes, and the date of acquisition was December 16, 2000. The scale of the photographs is 1: 5,000. A pair of photographs was scanned at 600 dpi (24 μm) resolution and quantified at 8 bits gray values. A flatbed scanner was employed assuming that the deformation induced during digitization was negligible.

Orthoimage Production. For this study we used PCI Geomatics® software. The process to obtain orthoimages and area determinations was as follows.

1. *Set projection*. The cartographic projection used was UTM, zone 14, line D121 and horizontal Datum NAD 27, for both orthoimage projection and GCP projection.

2. *Camera calibration information*. A Wild RC20, of 9" x 9" camera was used to take the photographs, with a focal

length of 153.10 mm and a distance between fiducial marks of 212.00 mm.

3. *Location of ground control points*. A set of 6 GCP was located on the corresponding images of the scanned pair of photographs. The GCP were obtained from Secretaría de Comunicaciones y Transportes. Once all GCP are gathered, a report of residual errors may be displayed; in this report, information about X and Y errors is available. By trial and error, the root mean-square error (rms) can be reduced by adjusting the GCP locations. The rms corresponding to GCP location was 0.5 pixels. After each GCP has been located it is also necessary to collect tie points. A tie point (TP) represents a surface feature easy to identify selected and marked as a reference point on the images.

4. *DEM generation*. OrthoEngine has several options to create a DEM; one of them uses the located GCP and TP of the previous step. DEM elevations are calculated from the parallax of the GCP and TP. For DEM generation, collection of match points is needed. A match point is an identifiable point on the images. In this case, 1000 match points were collected for DEM generation.

5. *Orthoimage production*. Once a DEM was generated, the orthoimage was produced. However, it is still necessary to apply a resampling routine. Resampling extracts and interpolates gray levels from the original pixels locations to corrected locations. This is achieved by applying a bilinear interpolation rule. This rule determines the gray level from a weighted average of the four closest pixels' to the specified input coordinates and assigns the value to the output coordinates.

6. *Area measurement*. The database containing the glacier boundaries was extracted from orthoimage and overlapped to a topographic database previously obtained from Secretaría de Comunicaciones y Transportes (Figure 2). This topographic base was made by using altitude contour lines extracted during photogrammetric processing; the altitude contours were fixed every 10 m. Further, a weighted average interpolation algorithm (Kriging) was applied to interpolate the contours and to generate the contours and calculate a rectangular grid with 5 m spacing. The errors introduced during DEM construction can be up to 1.5 m in a horizontal sense and 1.25 m in a vertical sense (Huggel and Delgado, 2000). The glaciated area (raw area) was extracted and measured using Surfer® (V.7) software. The glaciers of Popocatépetl volcano lie on a steep slope of 35º on the average. The calculated raw area was obtained as a planimetric surface. However, in order to get a realistic area, it is necessary to take into account the slope. Commonly, planimetric areas are obtained worldwide (C. Huggel and A. Kääb, personal communication), but the actual area eventually helps to estimate the ice volume if the thickness is known. Ice volume is the final objective for risk assessment because equivalent water volume can be estimated for flow generation modeling and simulation. The total glaciated area on December 16, 2000 was 209,138 m^2 (raw area), but considering the slope, real area is 255,310 m^2.

Error estimation. We assume that errors involved in the area estimation are statistically independent, because every step in image analysis is formally independent to each other. Errors related to camera lens and printing are negligible. To estimate the total error we considered the following errors: photo acquisition (E_1), digitization process (E_2) and, geocoding process (E_3). E_1 corresponds to the photographic resolution of the film employed: 7100 lines/cm (calibration report), therefore $E_1 = 0.007$ mm (0.035 m when taking into account the airphoto scale). E_2 was produced during the digitization process. The photos were digitized at 600 dpi, equivalent to 236 points/cm, and hence, E_2 is 0.020 mm (equivalent to 0.10 m). E_3 results from the georeferentiation process and corresponds to 0.524 pixel. If the pixel size is 5 m, the E_3 error corresponds to 2.6 m. Since E_1, E_2 and E_3 are independent, the total error is obtained by means of the following expression:

$$Et = \sqrt{(E_1)^2+(E_2)^2+(E_3)^2} \ . \qquad (1)$$

This equation yields a total error of ± 2.6 m, quite acceptable for the magnitude of glacial area changes. This figure represents 0.001% of the total area.

HAZARDS ASSESMENT

Lahar and flood generation are the main hazards originated by snow and ice melting during volcanic eruptions in the presence of ice bodies (Major and Newhall, 1989). The volume and range of the lahars depend on the available water. Thus, for hazard assessment at glacier-clad volcanoes the volume of equivalent water must be estimated.

In order to figure out the likely volume of a laharic flow produced by ice melting at Popocatépetl volcano, determination of equivalent water volume is needed. By using the value of 255,310 m^2 of glaciated area calculated above, and considering a mean ice thickness of 15 m, the ice volume is 3 829 650 m^3. Glacier ice density of 950 kg/m^3 (H. Delgado, unpublished data) is used to obtain the volume of equivalent water (3 638 167 m^3).

A lahar flow may contain 40% to 65% volume of water, and thus, laharic volume may be assessed. Lahars may be debris flows and hyperconcentrated flows. The first contain between 40% and 45% (Pierson and Scott, 1985; Pierson, 1986) volume of water, and the second, between 60% and 65% (Fei, 1993; Major and Pierson, 1992). Table 1 shows figures for maximum and minimum laharic volumes accord-

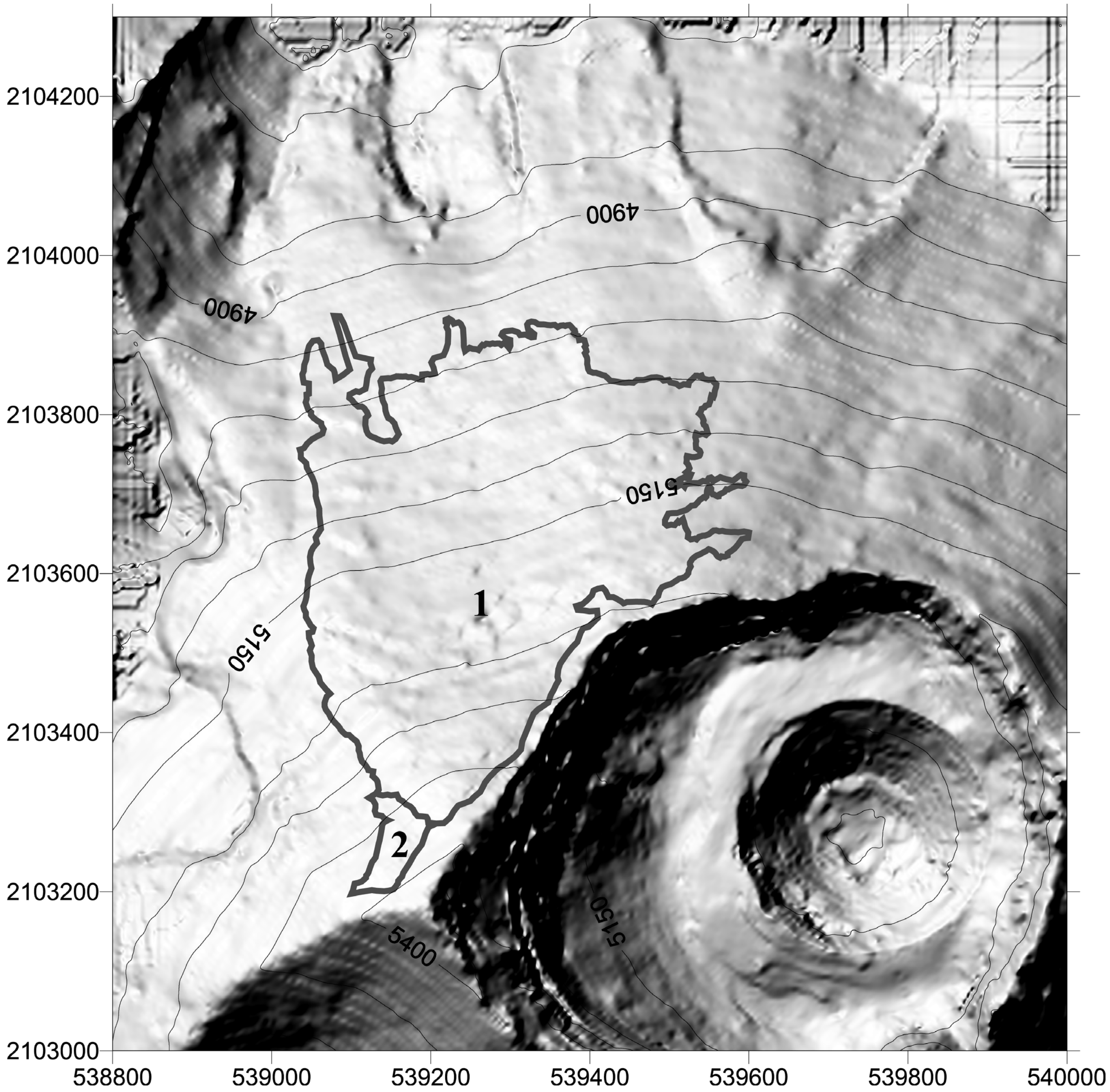

Fig. 2. Glaciated areas of Popocatépetl volcano (December, 2000); (1) Ventorrillo glacier, (2) Noroccidental glacier.

Table 1

Hypothetic volume of lahars by glacier melting

% Glacier melting	Volume lahar 40% water (m^3)	Volume lahar 65% water (m^3)
100	9.0 x 10^6	5.5 x 10^6
50	4.5 x 10^6	2.7 x 10^6
25	2.2 x 10^6	1.3 x 10^6
5	2.4 x 10^6	0.3 x 10^6

ing to different ice melting scenarios. Table 2 shows calculated volumes of documented laharic flows produced by ice or snow melting during eruption at volcanoes.

CONCLUSIONS

The use of digital photogrammetry for glacier monitoring is a useful tool, specially when a glacier is located on an active volcano. Volcanic activity implies a methodological change in glacier studies in order to protect researcher's life. Popocatépetl glaciers have changed strongly during the

Table 2

Laharic volumes for historic events

Flow type, Name	Location, Date	Origin	Flow volume (m^3)	Reference
debris flow San Nicolás Lahar	Popocatépetl volcano 1300 yr B.P.	snowmelt	7.0×10^7	González-Huesca (2000)
debris flow S. Fork Toutle R	Mt. St. Helens volcano USA, 1980	rapid snowmelt during eruption	1.3×10^7	Cummans, 1981
debris flow	Mt. Hood volcano USA, 1980	rainfall-and snowmelt- triggered landslide	7.6×10^4	Gallino and Pierson, 1985
debris flow Río Azufrado	Nevado del Ruiz volcano Colombia, 1985	rapid snowmelt during eruption	5.5×10^7	Pierson, 1986

current volcanic activity and, as a consequence, their monitoring is of great importance for hazard assessment.

Digital photogrammetry has important advantages. Small glaciers (such as Mexican glaciers) can be studied employing large-scale aerial photographs. This provides quantitative information about areas and volumes of glaciers in a relative short time allowing comparisons for different dates.

We show that measured areas can be obtained with an estimated error of ± 2.6 m. Taking into account the size of the measured areas (raw area 209 139 m^2 , real area 255 310 m^2) the error is acceptable.

Using the water equivalent data we can work out scenarios for hypotetical volume of lahars. Figure 3 compares the volume shown in Table 2 with the range of volumes estimated and shown in Table 1. This figure evidences that even a 100% melting of Popocatépetl's glacier should not generate a laharic event such as San Nicolás Lahar in terms of the estimated volume values, not even as Saint Helens or Nevado del Ruíz catastrophic lahars. A more likely ice melting of 25% would produce fairly small laharic events.

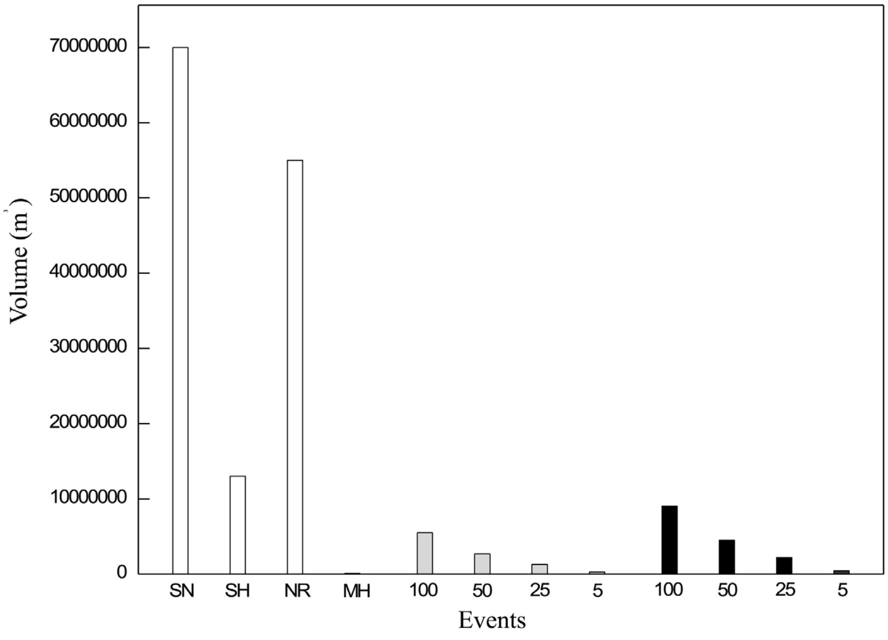

Fig. 3. Comparison of laharic volumes. SN: San Nicolás Lahar (Popocátepetl volcano); SH: South Fork Toutle river lahar at Mt. St. Helens volcano (Cummans, 1981); NR: Río Azufrado lahar at Nevado del Ruíz volcano (Pierson, 1986); MH: lahar at Mt. Hood volcano, 1980 (Gallino and Pierson, 1985). Numbers indicate percent melting of ice (gray for 65% water content in lahar and black for 40% water content).

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