Short-term Potential Volcanic Hazards at Popocatepetl, Mexico

Popocatépetl (smoking mountain in náhuatl) stands at the southern end of an 80 km-long chain that trends north-south and divides the basin of Mexico to the west from the basin of Puebla to the east. Popo is only 60 km southeast of Mexico City and 40 km west of the city of Puebla. The combined population of these two metropolitan areas exceeds 30 million inhabitants. The December 2000, activity of Popocatepetl has justifiably received intense public scrutiny.

The current dome growth and explosive activity present volcanologists and civil protection authorities with vexing problems that stem from our lack of a full understanding of the manner in which eruptions evolve at Popo. Large plinian eruptions have occurred at Popo with intervals ranging from 1000 to 3000 years and their ages are fairly well known. In contrast, the historic and geologic record of more frequent small to moderate eruptions is not as clear, and it may be difficult to forecast their occurrence and characteristics with accuracy. Important questions facing public safety officials at the moment revolve around prudent decisions based on the perceived effects of expected short-term events. What is the prognosis for the next few months and years?

Eruption History

Little is known about the early geologic history of Popo. The oldest rocks found so far at Popo have not been dated, but they are stratigraphically younger than rocks from Iztaccíhuatl volcano, immediately to the north. This suggests that the locus of magma production has migrated southwards during the course of time. Popo's present cone is not the first huge volcanic edifice that evolved at this site, as evidenced by at least three debris avalanche deposits that fan out towards the south (Siebe et al., 1995).

The most recent Mt. St. Helens-type collapse of the cone occurred ca 23,000 years ago and the resulting debris avalanche traveled more than 100 km to the south. Since then, the present cone started to grow. Activity during the past 20,000 years included at least 7 large Plinian eruptions that produced extensive pumice-and-ash fallout, pyroclastic flows, and lahars. Each of these eruptions produced ca. 5-10 km3 of fragmental material. The most recent of these explosive eruptions occurred within the period of human occupation about 5000, 2100, and 1100 yr. BP (Siebe et al., 1996) with devastating effects, as evidenced by numerous archaeological remains buried by pumice-and-ash as well as lahars. People have repeatedly repopulated the area because of the volcano's long repeat time and the availability of water and agriculturally productive soil. Recurrence of such a cataclysmic Plinian eruption in the near future would certainly represent a volcanic disaster of unprecedented dimensions in human history.

Volcanic activity between cataclysmic eruptions is poorly preserved in the stratigraphic record and/or difficult to date radiometrically. Since the Spanish conquest in the early 16th century, Popo has erupted several times but documentation of these events by witnesses is fragmentary and varies in quality (Waitz, 1921). These historic eruptions seem to have a common characteristic: Energy release was relatively gentle with repeated formation of small domes inside the summit crater. Related vulcanian explosions produced 1-10 km-high ash plumes with accompanying ashfall. Such activity lasted for several years to a few decades and no major damage or casualties were reported. The pattern of activity during one of these smaller eruptions is insufficiently understood to connect them with cataclysmic eruptions.

Present eruption and prognosis for the next 5 years

The present eruptive activity started on December 21, 1994 at 1.30 AM (local time). A dense ash plume rose in pulses from the crater floor followed initial vent-clearing explosions. Increased fumarolic and seismic activity during the prior two years led the news media and scientists to report increasing concern (Siebe et al., 1994; see also GVN Bulletins, 1994). During the first hours of the eruption, silt-sized ash reached several towns to the east and northeast of the volcano, including the city of Puebla. In the afternoon of Dec. 21, the government evacuated ca. 50,000 people from towns in the State of Puebla. These people spent almost two weeks, including Christmas and New Years, in shelters. During the second half of 1995 the emission of ash abated and almost ceased completely.

On March 5, 1996, ash emissions resumed with renewed intensity. By March 29, a new lava dome appeared in the crater. Within one month the lava had covered the entire crater floor to a thickness of at least 50 m. On April 30, a small vulcanian explosion from the dome blasted meter-sized boulders from the crater killing five mountaineers. Gravel 3 to 4 cm in diameter fell at a distance of 6 km, clasts as large as 0.5 cm fell on the roofs of Xalitzintla at a distance of 12 km, and sand-sized ash fell in Tlaxcala.

Since then, a total of 9 domes have formed in the crater. Dome growth is normally preceded and accompanied by harmonic tremor and increased fumarolic activity. At the end of each dome-building phase, vulcanian explosions partially destroy the dome and eject incandescent, ballistic boulders from the crater. The strongest explosion so far occurred on June 30, 1997, and not on Dec. 18, 2000, as propagated by the media. On both occasions, wind was blowing in the direction of Mexico City, where a thin coating of ash was deposited. In this context, the recent order to evacuate more than 40,000 people, as well as the coverage provided by the media, seems disproportionate.

The current eruptive episode began on December 12, 2000, and peaked with a vulcanian explosion on December 18. The pattern of this activity roughly matched that of June 1997. More than 40,000 inhabitants were requested to evacuate on December 16. Initially, only 15 % of the population followed this advice. The number of evacuees increased after the explosion of Dec. 18. The total number of evacuees in camps varies greatly according to different sources, but hardly reached more than 20,000 individuals. On Dec. 26 all were allowed to return home, since the activity had decreased.

Considering current and past activity, it seems probable that domes will continue to grow until the crater is entirely filled with lava. This might take at least a few more years at the current rate of dome emplacement. Once the crater is filled, lava will spill over the rim to the east and northeast, where the rim is lowest. The viscous lava will form short flows, the emplacement of which will be accompanied by small block-and-ash flows, which will not reach much further than ca. 5-6 km from the rim. This material might then become remobilized and form lahars similar in volume to the San Nicolás lahar (see Fig. 1). A major eruption (VEI 6-7) seems improbable at this time.

Probable hazardous events

In terms of the effects of the current eruptive episode on surrounding villages, the major hazard must be considered to be lahar. Relatively small, gravelly, lahars occurred at Popocatépetl about 1,300 years ago (Siebe et al., 1997). These monolithologic debris flows took place at a time when Popo's crater was completely occupied by a dome. Contemporaneous small lava flows and block-and-ash flows also spilled over the crater rim. This moderate activity preceded by about 200 yrs. the last major plinian eruption, which occurred 1,100 yrs. ago (Siebe et al., 1996).

These earlier lahars went down the Alseseca and Nexapa channels that drain the upper cone, originating downstream from a glacier (Figure 1). The San Nicolas lahar (Gonzalez-Huesca et al. 1997), between 1,100 and 1,300 years old, is one debris-flow deposit that probably formed when lava flows and block-and-ash flows emitted from the summit dome interacted with ice or snow. This flow traveled as far as 60 km from the source, following a path down the Alseseca channel that is currently inhabited by more than 30,000 people. Ceramic fragments in beds beneath this deposit suggest that the region was inhabited even at that time.

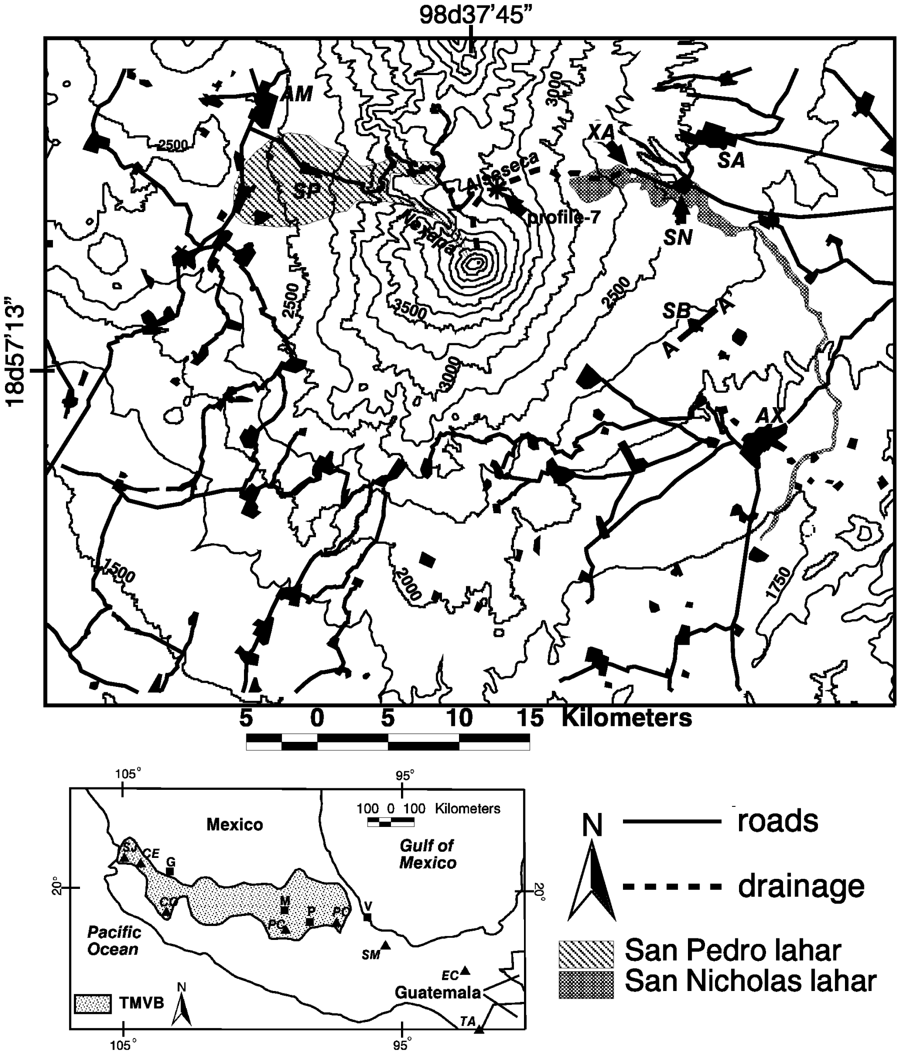

Fig. 1. Map of two lahars generated in the past 1200 years. The San Pedro lahars (SP)flowed to the west towards Amecameca (AM) and the San Nicolas lahar (SN)to the east initiated at the Alseseca channel. Cities shown include: Atlixco (AX) Xalitzintla (XA) San Baltazar (SB), San Pedro (SP), and San Andreas (SA). Inset shows location of Popo (PC)and other active volcanoes as triangles. Cities, such as Mexico City (M) and Puebla (P) are squares.

On the night of June 14, 1997, a debris flood was observed near the village of Santiago Xalitzintla, c. 13 km from the summit in the Alseseca channel, which had previously been dry. The flood filled the stream channel with debris, but there were no important consequences for the town.

Early on July 1, 1997, a second, larger debris flow reached Xalitzintla, on the day following the largest eruption to date. Although some rainfall was reported at Amecameca in the days prior to the flow, no rainfall apparently had been seen in Xalitzintla. No precursory flooding occurred in the channel. The debris flow inundated cultivated areas and flooded a house on the margins of the channel. Both flows originated near the outlet tongue of the Ventorillo glacier, at an elevation of c. 4800 m. By the time of inspection (January, 1998) the glaciers showed noticeable ablation, lacking marginal ice-cliffs that had been apparent in 1995.

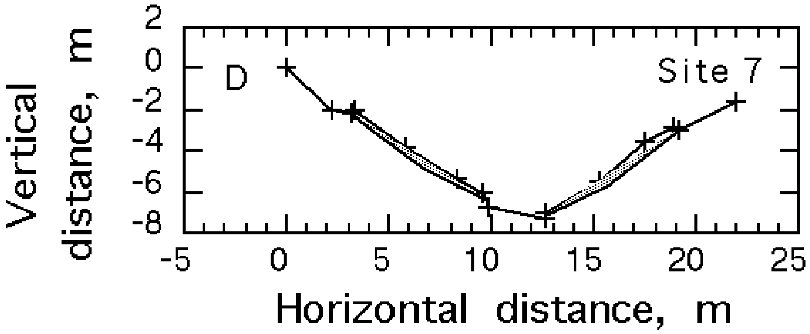

Fig.2 Cross section through the Xalitzintla lahar at section 7 shown in Fig. 1.

The 1997 deposits and erosional scars generally occupy the lowermost several to ca. 10 m of the channel at distances to ca. 12 km from the glacier terminus, except where the basal channel cross section broadens. At most proximal localities, the deposits are fines-depleted, clast-supported gravels, with a matrix of medium-coarse sand. Boulders within the deposit are up to 4 m in maximum diameter. Most of the deposit occurs as levees at the high-water trimline approximately 10 m above the channel floor in many localities, and at a second trimline several meters above the channel floor. Inboard of the trimlines, material has been eroded. At distances of 12 to 17 km from the glacier terminus, the debris flow deposit is mud-rich, and fills a broad rectangular channel to a depth approaching 1 m. The available data are all consistent with the floods originating at least in part from melting of glacial ice by pyroclastic debris.

Table 1. Data for mapped lahars.

Deposit/Locality	**Date**	**Thickness (m)**	**Planimetric area (m^2)**	**Volume* (m^3)**
Xalitzintla	1997	1	3.3 x 10^{5}	3.3 x 10^{5}
San Nicholas	1100-1300 years ago	2	2.5 x 10^{7}	5.0 x 10^{7}
San Pedro	1100-1300 years ago	2	5.9 x 10^{7}	1.2 x 10^{8}

*Based on average thickness x planimetric area
N.D. = No Data

How much water is available in the glacier for melting? Glacier surveys conducted in April 1995 showed that the ice then covered a surface area of 0.559 km^2 (Delgado, 1997). The western third of the ice mass has very few crevasses. A thickness of 10 - 20 m was estimated using a digital elevation model of nearby bedrock contours intersecting the glacier, and is consistent with an estimate derived from glacier flow theory using an effective yield stress of 100 KPa for the observed glacier slope of about 25 degrees. The central and eastern portion of the main ice mass is heavily crevassed, suggesting that the ice is thicker than 20 m on average. Ice motion of ~2 cm/day measured from ground surveys conducted with the total station is consistent with a glacier of average thickness 30 to 40 m. Measurements of the ice thickness in the central portion of the ice mass were taken using a monopulse radar. Depths of 40 to 60 m were obtained on the centerline of the main mass. Minimum depths were also estimated by sounding crevasses and surveying marginal cliff heights where possible. The marginal cliffs near the glacier terminus range from 5 to 10 m high where the ice is apparently moving. Thus the ice thickness probably varies from about 10 to 60 m, with an average thickness of 40 m. The total volume of ice is then 2.8 x 10^7 m^3.

Numerous observations from the 1985 Nevado del Ruiz eruption have shown that large amounts of meltwater can be rapidly produced by mechanical erosion of a glacier by pyroclastic density currents (Thouret, 1990). Photographs taken of the glaciers following the eruptions show clearly the presence of 100 m long furrows or grooves, several meters wide and deep over parts of the glaciers. Other sections of the glaciers showed evidence of smoothing of seracs by pyroclastic currents. The snout of one glacier, and hanging glaciers within another valley were removed by ice avalanching that may have been caused by the earliest pyroclastic currents. In other areas there is evidence of energetic glacial drainage following the earlier pyroclastic flows. Mechanical ablation probably accounted for 10 to 15 m of glacier thinning in some localities, while up to 32% of the volume of the glaciers was removed, perhaps not all by pyroclastic erosion. A reasonable estimate of the amount of water in Popo's glacier that is available for melting during eruption might therefore be ca. 1×10^7 m^3.

Computer simulations of hazardous areas

Simulation of pyroclastic flows and rock avalanches used the FLOW3D code (Sheridan and Kover 1997) that provides velocity histories of particle streams along flow paths in three dimensions. The algorithm for the flows uses parameters for basal friction and viscosity similar to those of McEwen and Malin (1990). FLOW3D simulations were used to create the hazard map at Popocatépetl (Macías et al. 1995) and Volcán Colima (Martin del Pozzo et al. 1995). Fig. 3 models the Merapi-type block-and-ash flows that might occur at Popo using a model basal friction coefficient of 0.09 and a viscosity parameter of 0.01. Bit-mapped and color coded overlays of multiple themes, including the flow paths and velocities, were produce a realistic image useful for non-professional observers. The interactive platform of FLOW3D allows the observer to adjust the perspective and distance for the desired view. The use of cities and towns as a layer in the model allows the estimation of sites of potential loss of life and property.

Volcanic debris flows related to various sources eventually follow major river systems. For Popo the Alseseca and Nexapa channels constitute these systems. Iztaccíhuatl and remnants of the ancient Popo edifice block flows from the upper flanks that are then diverted to the east or west at the Paseo de Cortéz down the two major channels. Assuming likely source areas, particularly on the northern flank, inundation zones for lahar volumes of 10^7 and 10^8 m^3 were simulated with ArcInfo using the LAHARZ model developed by Iverson et al. (1998). Their GIS code calculates flow cross sectional areas to plot the width of the peak flow in the river valleys and uses planimetric area to map the flow extent. Figure 4 shows inundation wave heights at San Baltazar computed by this code. The source areas for the debris flows were based on energy cone modes using FLOW3D code. The smaller volume model lahar represents the water available from glacier ablation by pyroclastic flows and the larger volume represents the water from complete melting of the current glaciers. Compare these volumes to the size of the prehistoric lahars of Table 1.

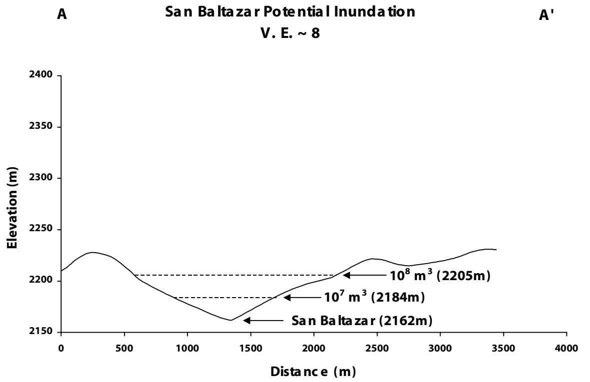

Fig. 4. Cross section at San Baltazar (see Fig. 1 for location) showing the inundation levels for 10^7 and 10^8 m^3 lahars predicted by LAHARZ.

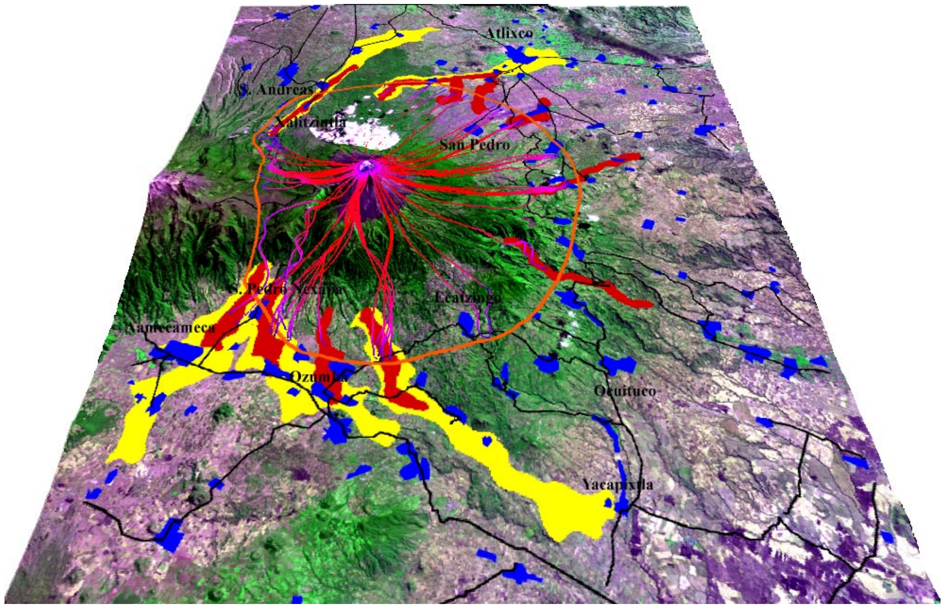

Fig. 3. *Computer simulation of potential pyroclastic flow and lahar distributions*.

Conclusions and Recommendations

Conclusions:

- The volcanic activity will slowly evolve as the crater fills with lava, unless it ends as the last historic events that lasted 9 years from 1919 to 1927.
- Rock avalanches and pyroclastic flows could produce source materials for lahars
- The maximum possible lahar, based on the size of the glacier, is about 10^8 m^3.
- Models show that future lahars would threaten the same general areas affected by lahars in the past several hundred years.

Recommendations:

- Interpretation of small events such as Merapi-type block-and-ash flows and short-term expected lahars require a much better topographic data set than is currently available. In this regard SRTM data would be particularly useful in model construction, visualization, and analysis.
- New models are needed that can better simulate small flows of 10^6 to 10^8 m^3. These models should include erosion and deposition from the flows and should respond to topographic elevation differences of 10 m or less.
- Animated visualization of the simulated hazards is needed to help civil protection authorities and the general public to understand the risk involved in specific inhabited areas.

Acknowledgements

This work was partially funded by NASA grant NAG57579 and NAG53142. Work by Siebe and Macias was funded by grants to C. Siebe from CONACYT (27993-T and 27994-T) and UNAM-DGAPA (IN 101199). Information on the glaciers and 1997 events was collected in conjunction with Melinda Brugman and Hugo Delgado. Facilities at the National Center for Geographic Information Analysis were used for GIS analysis. The Center for Computational Research at UB was supportive in developing visualization models.

Authors

Michael F. Sheridan, Bernard Hubbard, and Marcus I. Bursik, University at Buffalo, Buffalo USA; *Claus Siebe,* UNAM, Mexico; *Michael Abrams,* Jet Propulsion Laboratory, Pasadena, USA; *Jose Luis Macias and Hugo Delgado*, UNAM, Mexico. For additional information, contact Michael Sheridan at mfs@geology.buffalo.edu

References

Gonzalez-Huesca, A.E., H. Delgado, and J. Urrutia-Fucugauchi, The San Nicolas lahar at Popocatepetl volcano (Mexico): a case study of a glacier-ice-melt-related debris flow, triggered by a blast at the outset of a plinian eruption. *Proc. IAVCEI*, Puerto Vallarta, p. 94, 1997.

Iverson, R. M., S. P. Schilling, and J.W. Vallance, Objective delineation of lahar-inundation hazard zones, *Geol. Soc. Amer. Bull. 110 (8),* 972-984, 1998.

Macías, J.L., G. Carrasco-Nuñez, H. Delgado, A.L. Martin, C. Siebe, R. Hoblitt, M.F. Sheridan, and R.I. Tilling, Mapa de Peligros del Volcán Popocatépetl. Mapa e Informe técnico al Comité Científico Asesor de la Secretaría de Gobernación, *UNAM-CENAPRED*, Map with explanation booklet, 14 p, 1995.

Martin del Pozzo AL, M.F. Sheridan, D. Barrera, J.L. Hubp and L.V. Selem, Mapa de Peligros Volcán de Colima, *Instituto de Geofisica, UNAM*, México, 1995.

Siebe, C., M. Abrams, J.L., Macías, and J. Obenholzner, Repeated volcanic disasters in Prehispanic time at Popocatépetl, Central Mexico: Past key to the future? *Geology*, *24*(5), 399-402, 1996.

Siebe, C., P. Schaaf, and J. Urrutia-Fucugauchi, Mammoth bones embedded in a Late Pleistocene lahar from Popocatépetl volcano, near Tocuila, Central Mexico. *Bull. Geol. Soc. Amer*., *111*(10): 1550-1562, 1999.

Siebe, C., J.L. Macías, M. Abrams, M., S. Rodríguez-Elizarrarás, R. Castro, and H. Delgado, Quaternary explosive volcanism and pyroclastic deposits in east central Mexico: Implications for future hazards. *In*: J. Chacko (Ed.): *Guidebook for the 1995 Annual Meeting of the Geological Society of America,* New Orleans, Louisiana, p. 1-47, 1995:

Sheridan M.F., T. Kover, FLOW3D: A computer code for simulating rapid, open-channel volcanic flows: *Proc. UJST workshop on the Technology of Disaster Prevention against Local Severe Storms*, Norman OK. 155-163, 1996.

Sheridan M.F. and J.L Macías, Estimation of risk probability for gravity-driven pyroclastic flows at Volcán Colima, México. *J. Volcanol. Geotherm. Res.*, *66*, 251-256, 1995.

Thouret, J-C., Effects of the November 13, 1985 eruption on the snow pack and ice cap of Nevado del Ruiz Volcano, Colombia, Williams, Stanley N. (editor), Nevado del Ruiz Volcano, Colombia; I, *J. Volcanol. Geotherm. Res. 41* (1-4), 177-201, 1990.

Waitz, P., Popocatepetl again in activity, *Am. J. Science* 5th Ser., *1*, 81-85, 1921.

White, S.E., The firn field on the volcano Popocatepetl, Mexico, *Journal of Glaciology 2*, 389-392, 1954.