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Editorial

The 1994–present eruption of Popocatépetl volcano: Background, current activity, and impacts

1. The volcano and the challenge

Popocatépetl volcano (*smoking mountain* in native *Náhuatl* language), 5450 m high, is one of the highest active volcanoes in North America. After nearly 70 years of quiescence, it began a new episode of activity in December 1994. Since then, this still-continuing eruption has attracted the attention of volcanologists around the world because of its intriguing peculiarities, particularly its exceptionally huge gas output (Delgado-Granados et al., 2001), given its rather modest magma production rate characterized by a sequence of lava dome emplacement and destruction.

Popocatépetl's long-lived eruption has also commanded the attention of the public and the Civil Protection authorities because it is located in a densely populated region, just 70 km from the downtown of Mexico City, and 40 km from the city of Puebla, with hundreds of towns and villages within 60 km from the volcano (De la Cruz-Reyna and Siebe, 1997; Sheridan et al., 2001). Even though nobody lives within 10 km of the crater, ~500,000 people live within 10–30 km, and nearly 1,300,000 within 40 km (De la Cruz-Reyna and Tilling, this issue). Moreover, within 40–80 km from the vent, more than 20 million inhabitants may be exposed to the effects of a large-magnitude explosive eruption, which fortunately has not occurred in post-Hispanic times, but has occurred repeatedly in pre-Hispanic times as evident from the volcano's eruptive history, and archaeological findings (Plunket and Uruñuela, this issue). Popocatépetl's eruptive activity and its socio-economic and human impact have drawn unprecedented interest of the national and international media, which in turn have complicated the process of communication of the real hazard levels.

Post-1994 geological studies of the deposits of plinian eruptions (e.g., Siebe et al., 1995, 1996, 1999; Panfil et al., 1999) indicate that during the past 5000 years, the volcano has erupted energetically at least 4–5 times. However, the historical records contain no mention of large-scale eruption in the past 650 years (Casanova Becerra et al., 1987; Delgado-Granados et al., 1988; De la Cruz-Reyna et al., 1995). Most eruptions in recent centuries have been relatively mild, effusive eruptions with some vulcanian events (with the possible exception of the eruption in 1663–1664; Guzmán Peredo, 1968).

A good knowledge of the eruptive history of a volcano—especially as regards eruption size, explosivity, frequency, and environmental impact—constitutes an essential component for the assessment of the potential hazards and the calculation of the probabilities for their recurrence in a given time interval. Worldwide experience shows that, unless there are sufficient data to indicate otherwise, the present or future behavior of a volcano is most likely to resemble its behavior in the geologic past. Hence, the phrase "the past is the key to the future" is commonly invoked in volcanology and other earth sciences dealing with potentially destructive natural phenomena. Experience worldwide also demonstrates that the quality and reliability of hazards assessment, as well as volcano monitoring and eruption forecast (long-term and short-term) require an integral approach involving numerous disciplines. However, such integration of scientific information to reduce volcano risk is a time-consuming process, one that also can be demanding and challenging, particularly under the high-stress conditions during a rapidly escalating volcanic crisis.

We hope that the research results published herein may be useful for the generation and evaluation of eruption scenarios, for guiding expanded volcano monitoring efforts, and for improving the forecast capabilities of the possible eruptive behavior at Popocatépetl or any other potentially active volcano with similar characteristics. Equally important is the setting of realistic constraints on possible evolution of the ongoing eruptive activity. These constraints represent important decision factors for the responsible civil authorities, particularly if they are expressed as low probabilities of dissimilar scenarios. Indeed, the socio-economic and human cost of overreactions by government in economical and reliability terms may sometimes be as high as that of governmental indifference or inaction in responding to volcanic unrest.

Popocatépetl provides an excellent example of how the perception of risk is strongly influenced by the recent eruptive history and not by a full geological record, particularly among the people dwelling in the endangered areas and the media. None of the written records describing the historical eruptions of the past seven centuries mention any large, destructive eruptions. The maximum magnitudes or intensities of eruptions occurring in that period did not exceed VEI 3, that is, levels

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quite comparable to that of the current eruption. Apparently, some early Spaniards were impressed by the large amount of sulfur in Popocatépetl's summit crater and actually descended into it to collect sulfur for use in making gun powder. For example, a famous anecdote describes the Conquistador Hernán Cortés sending his master cannoneer Montaño y Mesa into the crater to collect sulfur: Soldiers made a winch using about 60 m of rope from the Cortés' ships, and Montaño y Mesa descended 7 times to the crater floor to collect about 100 kg of sulfur—presumably sufficient to make enough gun powder to continue his campaigns, as described by Cervantes de Salazar in 1554 and Díaz del Castillo in 1575 (Magallon, 1971; Ramírez-Cabañas, 1974; Dr. Atl., 1939). Assuming that the abundance of sulfur condensate at Popocatépetl's summit provides a qualitative measure of volcano degassing, it is tempting to speculate that perhaps the early historical eruptions may also have been accompanied by high volcanic gas output as well documented for the current eruption.

Perhaps the largest event of the historical eruptive record occurred in February 24, 1664, when a volcanic explosion (probably vulcanian?) caused windows and doors in Puebla to burst open, as well as the collapse of a small sector of the crater rim leaving it cusped (Casanova Becerra et al., 1987; Delgado-Granados et al., 1988; De la Cruz-Reyna et al., 1995). However, no damage was reported, not even in the nearest towns. Nevertheless, as clearly shown by recent studies, Popocatépetl produced much more powerful eruptions in the geologic past. In addition, archeological findings at sites in the northeastern sector of the volcano (Plunket and Uruñuela, this issue) demonstrate that the prehistoric eruptions of Popocatépetl volcano severely impacted the pre-Hispanic populations at the time.

Prior to 1994, Popocatépetl was weakly and intermittently active during the years 1919–1927, after which the volcano remained in a fumarolic stage. After 1927, no mountaineer or geologist reported any subsequent eruptive activity or anomalous behavior. However, in 1940 and again in 1985, glowing areas ringing some fumarolic vents were observed at night, although no incandescence was seen during the day (Casanova Becerra et al., 1987). By the year 1986, reconnaissance work to sample fluids was done by rappelling into the crater, which at that time had an elliptical configuration (800 by 600 m and 100–400 m deep). Popocatépetl started to show signs of increasing unrest in the fall of 1990, when exceptionally large vapor plumes billowed up from its crater (Delgado-Granados et al., 2001). During the following 3 years, the fumarolic activity was observed with greater frequency.

Not surprisingly, when a large, long-dormant volcano such as Popocatépetl—located so close to major population centers—reawakens and begins to erupt, effective communications with the authorities, the populace at risk, and the media pose a major challenge. Perhaps, one of the best ways to confront this challenge is to build mutual understanding and trust among all the parties involved. This means that scientists should put themselves in the shoes of authorities and vice versa. In this way, authorities understand the importance of sustained comprehensive monitoring, as well as the limitations of forecasting. On the other hand, scientists must understand that the decisions of the officials strongly depend on what they say, and how they say it. Thus, the responsibility of such decisions is shared, even though the civil authorities have the legal mandate to prepare contingency plans and take mitigative countermeasures, including evacuations.

At Popocatépetl, an impressive effort to study and monitor the volcano was mounted in the midst of a strong economic depression (between 1994 and 1996). Funding from the Civil Protection, and scientific research entities (mainly the National Council for Science and Technology and internal funding from the National Autonomous University of Mexico) allowed the purchase, deployment, and maintenance of networks and systems with the valuable help of external organizations such as the U.S. Geological Survey and the Japan International Cooperation Agency.

Dealing with a complex volcano like Popocatépetl represents a formidable challenge. Even though there are many diverse efforts focused in the understanding of the eruptive mechanisms and emplacement of eruptive products, as well as the precursors impending eruptions, it is still difficult to give a precise assessment for the developments of the eruptive activity in the near-, mid-, or long-term future. Nonetheless, the now-available knowledge about this volcano, as compared with what was known in 1994 is huge in spite of the deficiencies.

This special issue comprises a series of studies that partially represent the types of investigations undertaken at Popocatépetl volcano. They shed light on the understanding of the volcano's internal dynamics and eruptive system, as well as giving a clearer picture of its eruptive history. Below we briefly highlight the topics covered in the papers of this Special Issue and their importance.

2. Seismicity and deformation

De Barros et al. analyze Rayleigh waves recorded by broad-band seismographs on Popocatépetl volcano; they measure Rayleigh-wave phase velocities and invert them for constraining the crustal structure below the volcano. This paper presents new results based on previously unexplored data and helps to expand and clarify information to previous models of the Trans-Mexican Volcanic Belt's crustal structure.

The paper by Arciniega-Ceballos et al. describes the seismic activity of Popocatépetl volcano during a deployment of a dense network of broad-band seismometers, recognizing three families of seismic events and classifying them using a correlation method. Source mechanisms are then proposed for those events, based on waveform inversions and comparisons carried out by Chouet et al. (2005) for two explosions and using the similarity with their records.

The article by Cabral-Cano et al. demonstrates that Popocatépetl appears to be an active volcano for which deformation is either non-existent or undetectable with the resolution of the monitoring techniques used. Their findings are timely because they contrast with those of numerous recent studies of other volcanoes that show clear evidence of deformation associated with eruption activity. Thus, it is very important to recognize what is visible and detectable from the volcano under ongoing continuous activity by using recent well-developed technology such as the GPS. The authors' conclusion underscores the wide diversity in the behavior of volcanic systems and the need to carefully consider different types of instrumentation in choosing the optimum monitoring strategy. This study at Popocatépetl emphasizes the critical need for more observational experiences, employing multiple methods, in monitoring volcano deformation.

3. Volatile emissions, spring waters and ashes

Armienta et al. describe a rich data set of water analyses obtained from Popocatépetl volcano over nine year period. The compositional variations are interpreted as the result of volcanic gas absorption and changes in water/rock interaction. Chemical changes linked with volcanic activity were produced either from direct interaction of volcanic gases with aquifers or from the opening of new pathways dissecting the volcanic edifice induced by reactivation of faults. Some chemical species like boron, and chloride show short-period fluctuations, while others like CO_2 reflect a slow accumulation process. Systematic sampling of spring water provides an important geochemical monitoring method that provides clues to the internal state of the volcano and may detect early precursors of the volcanic activity.

Larocque et al. show very interesting data on the volatility of metals from magmas; they describe a complex gold-bearing assemblage within recent pumice samples, attributed to precipitation of a magmatic volatile phase. The authors were fortunate for identifying these mineral assemblages despite their extremely low concentrations, and for circumventing the potential sample preparation and analytical problems. Their findings directly strengthen the widely believed, but poorly documented, relationship between precious metal deposits and a magmatic source for the metals (as stated in the introduction), and the role played by vapor transport.

Martin Del Pozzo et al. briefly characterize the extent and dispersal of ash from Popocatépetl volcano, in particular during the explosive eruptions of 1994–1997. The paper is a useful contribution in that it documents several new isopachs for specific eruptive events and presents a summary of the estimated volumes of erupted ash.

Techniques for monitoring volcanic activity by means of satellite imagery and remote sensing are becoming more widely applied, complementing traditional observations. Matiella et al. explore the detection and quantification of SO_2 concentrations in volcanic clouds by such means. They show direct comparisons of MODIS data with COSPEC measurements, as well as a comparison between SO_2 abundances and ash abundances. Their algorithms show the viability of applying remote sensing techniques to the detection of ash and SO_2 emissions. Popocatépetl is an active, well-monitored volcano that affords a locale for testing such techniques, particularly during the dry season (December-May) when interference with water vapor in clouds is minimal.

4. Glaciers and lahars

Julio-Miranda et al. describe the complex interactions that take place between the eruptive activity and the glacier at Popocatépetl volcano and show that a significant consequence of such interactions is the enhancement in glacier volume. Logistical difficulties and safety considerations preclude making direct measurements in the field. Thus, the study utilizes digital photogrammetry applied to aerial photographs of the volcano and the construction of digital elevation models (DEM) to determine the glacier changes. The authors present a model of the evolution of Popocatépetl's glaciers based on the distribution, rate, and magnitude of the glacier changes caused by the eruptive activity of Popocatépetl volcano during 1994–2001. This contribution is very timely because of increasing recent interest on volcano–ice interactions.

The paper by Huggel et al. evaluates digital elevation models (DEM) constructed from different sources for their applicability to assessment of risk from lahars. An important finding is that grid spacing does have an effect, as indicated by results from consideration of two DEMs (SRTM and ASTER) with different grid spacings. A thorough discussion of the relationship between lahar volume and the H/L ratio is given, including a plot of lahar volume vs. H/L built from data compiled from the literature and from this study. Both parameters are specified as inputs to both models, and the two quantities then are related. The data is rather inhomogeneous, however, and reflect the wide variation in flow phenomena observed in nature.

5. History and public response

Plunket and Uruñuela present innovative work describing the results of several seasons of archeological excavations. They describe their findings at sites in the Tetimpa region on the northeast flank of Popocatépetl, consisting of distinct houses and agricultural fields buried repeatedly by the tephra from the volcano between 2000 years BP and 900 AD. They show that the eruptions from Popocatépetl volcano clearly had adverse impacts on the populations at the time. Volcanic eruptions worldwide have been claimed as agents responsible for natural disasters that cause destruction of cities, famine, mass migration, and other societal disruptions. Within this context, this paper provides a comprehensive account of the consequences of the eruptions of Popocatépetl on smaller human settlements in pre-Hispanic times and the implications for the reconstruction of their histories. This thoughtful work prompt us to wonder if massive eruptions, such as those from Popocatépetl, might induce major sociological adjustments between the larger numbers of "slave" laborers, suddenly dispossessed by a volcanic disaster, and the ruling classes needing workers for monumental constructions.

The final article is an analysis of the ongoing Popocatépetl volcanic crisis. De la Cruz-Reyna and Tilling address the problem of attaining a perception of risk as uniform as possible amongst a population of millions of inhabitants during the development of an eruption. One approach is to design a communications tool that describes—as clearly and simply as possible—the state of the volcano, the more likely scenarios corresponding to such activity, and the recommended level of response. In the case of Popocatépetl, this tool has been called the *Volcanic Traffic Light Alert System* (VTLAS). It is basically a protocol that translates the volcano threat into levels of preparedness for the emergency-management authorities based on the probability of possible scenarios. In analyzing and learning from the Popocatépetl experience, this contribution is intended to serve volcanologists and authorities involved in crisis situations analyzing the Mexican experience.

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