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Journal of Volcanology and Geothermal Research 170 (2008) 121–134

Journal of volcanology and geothermal research

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# Scientific and public responses to the ongoing volcanic crisis at Popocatépetl Volcano, Mexico: Importance of an effective hazards-warning system

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Received 6 September 2007
Available online 16 September 2007

## Abstract

Volcanic eruptions and other potentially hazardous natural phenomena occur independently of any human actions. However, such phenomena can cause disasters when a society fails to foresee the hazardous manifestations and adopt adequate measures to reduce its vulnerability. One of the causes of such a failure is the lack of a consistent perception of the changing hazards posed by an ongoing eruption, i.e., with members of the scientific community, the Civil Protection authorities and the general public having diverging notions about what is occurring and what may happen. The problem of attaining a perception of risk as uniform as possible in a population measured in millions during an evolving eruption requires searching for communication tools that can describe—as simply as possible—the relations between the level of threat posed by the volcano, and the level of response of the authorities and the public. The hazards-warning system adopted at Popocatépetl Volcano, called the *Volcanic Traffic Light Alert System* (VTLAS), is a basic communications protocol that translates volcano threat into seven levels of preparedness for the emergency-management authorities, but only three levels of alert for the public (color coded green–yellow–red). The changing status of the volcano threat is represented as the most likely scenarios according to the opinions of an official scientific committee analyzing all available data. The implementation of the VTLAS was intended to reduce the possibility of ambiguous interpretations of intermediate levels by the endangered population. Although the VTLAS is imperfect and has not solved all problems involved in mass communication and decision-making during a volcanic crisis, it marks a significant advance in the management of volcanic crises in Mexico.

*Keywords:* Popocatépetl; volcano hazards; volcano monitoring; warning system; volcanic-emergency management; risk perception

## 1. Introduction

Popocatépetl Volcano is located in the central Mexican Volcanic Belt (Fig. 1) within a densely populated region, with over 20 million people vulnerable to direct hazards associated with a major explosive eruption. Situated about 70 km southeast of downtown Mexico City, Popocatépetl is arguably the most dangerous volcano in the country. This 5454-m-high volcano's geologic past clearly indicates that it is capable of producing catastrophic eruptions: three Plinian events have occurred within the past 5000 years B.P., well within the period of human settlement in central Mexico (Siebe et al., 1996; Siebe and Macías, 2004). Fortunately, to date the current eruptive episode—beginning in December 1994 after being dormant for nearly six decades—has consisted of relatively minor activity, which has characterized Popocatépetl's activity since the 14th century (De la Cruz-Reyna et al., 1995). Nonetheless, given the huge population potentially at risk, together with concerns about possible escalation of eruptive activity, the management of the ongoing "volcanic crisis" at Popocatépetl (CENAPRED-UNAM, 1995) has posed, and continues to pose, a major challenge for volcanologists, national and local civil authorities, and the affected public.

The effective management of a volcanic crisis usually involves several integral components, which in most cases, may be

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doi:10.1016/j.jvolgeores.2007.09.002

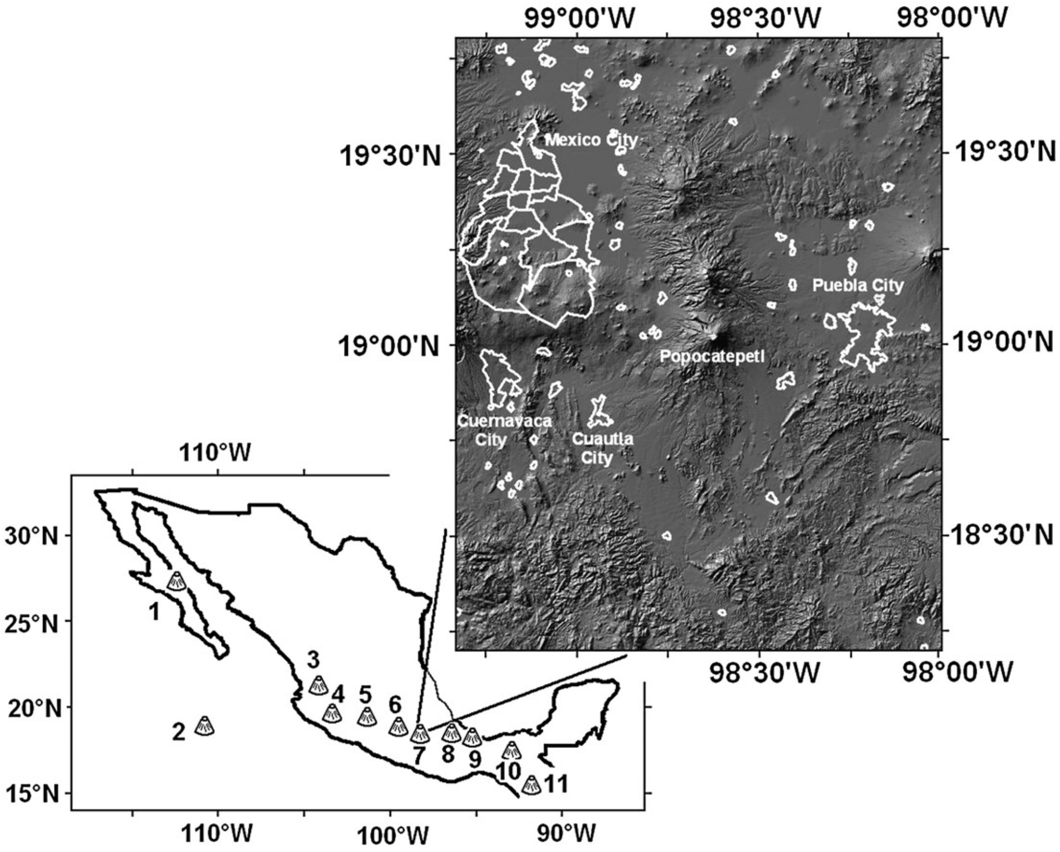


Fig. 1. Location of Popocatépetl. The insert shows the distribution of cities within 100 km of the active crater. The cities of Mexico, Puebla, Cuernavaca, Cuautla and others located in the insert sum up a population over 20 million. Some of the volcanoes of Mexico with historical activity are shown in the map: 1. Tres Vírgenes; 2. Evermann (Socorro); 3. Ceboruco; 4. Colima; 5. Paricutin; 6. Xitle; 7 Popocatépetl; 8. Pico de Orizaba (Citlaltépetl); 9. San Martín Tuxtla; 10. El Chichón; 11. Tacaná.

aggregated into three main elements (De la Cruz-Reyna et al., 2000):

a) Identification of the areas threatened by a given volcano, together with the definition of the probabilities that specific hazardous volcanic phenomena may occur in a given interval of time. This generates a static view of the potential hazards posed by the volcano showing unrest, most commonly represented as a hazards-zonation map.
b) Geophysical, geochemical, and remote-sensing monitoring of the restless volcano—in real time to the extent possible—to document its changes in state and to assess the level of associated potential hazards. To be useful, scientific information on the volcano must be interpreted and translated in terms of hazard scenarios, including the possibility of the escalating unrest culminating in eruption, nature and size of the anticipated eruption, the extent of hazardous processes, etc. The data from volcano monitoring provide the only scientific basis for making a dynamic estimate of the probability of occurrence of specific scenarios in the short term. The reliability and usefulness of such scenarios critically depend on the quantity and quality of the monitoring data, and on the ability of the members of the scientific teams to exchange opinions, compromise ideas, and reach a consensus.
c) Development and implementation of a hazards-warning system and response scheme that allow the civil authorities and vulnerable population to adopt mitigation measures according to pre-established levels of risk. An effective communication and warning system should be able to generate a similar level of awareness and perception of the

Table 1
Volcanic explosivity indexes of known eruptions of Popocatépetl Volcano reported from the 16th century to present. (Adapted and updated from De la Cruz-Reyna et al., 1995)

| Year | VEI |
|---|---|
| 1512 | 2 |
| 1519 | 3 |
| 1539–1540 | 2 |
| 1548 | 2 |
| 1571 | 2 |
| 1592 | 2 |
| 1642 | 2 |
| 1663 | 2 |
| 1664 | 3 |
| 1665 | 2 |
| 1697 | 2 |
| 1720 | 1 |
| 1804 | 1 |
| 1919–1920 | 2 |
| 1921 | 2 |
| 1925–1927 | 2 |
| 1994–1997 | 2 |
| 2000 | 3 |
| 2001–present | 1–2 |

> changing risk among the scientific team responsible for assessing possible outcomes of the volcanic activity, the decision-making authorities, and the threatened population.

The first two elements have been extensively addressed in several recent summary works (e.g., McGuire et al., 1995; Scarpa and Tilling, 1996; Sigurdsson et al., 2000; and references cited therein); these two elements as applied specifically to Popocatépetl are the topics of most other papers in this *Special Issue*. Here, we focus primarily on the challenges involved in the design of a hazards-warning and response scheme that may at least perform satisfactorily in a crisis situation in which the potential risk of a major eruption could affect one of the largest concentrations of population in the world.

Popocatépetl is one of the ten most populous active volcanoes in the world and the only one of the ten in the Americas; the other nine are all located in Indonesia or Japan (Small and Naumann, 2001, Table 1). Analysis of the "Mapa de Planeación de Emergencias para el Volcán Popocatépetl" ("Map for Popocatépetl volcano emergency management of the National System of Civil Protection of Mexico") shown in Fig. 2, as well as other sources (e.g., Macías et al., 1995a,b; Siebe et al., 1996; Sheridan et al., 2001; Siebe and Macías, 2004), shows that the densely populated areas northeast of the volcano, including México City, the capital of the country (~17,000,000 population), may be significantly affected by ashfalls. Other areas may be ashfall-prone as well. Popocatépetl is only about 45 km west of the city of Puebla, capital of the state of Puebla (~1,350,000 population), which may be affected by ashfall hazard to even a greater extent under particular wind conditions.

The state of Puebla has a total population of about 5.1 million, and about 4% of that population live around the volcano and are at risk from direct effects of a major eruption. To the south of the volcano, in the state of Morelos, a similar proportion (4–5%) of its 1.56 million may also be vulnerable to direct impacts of a major eruption. In addition, Morelos state contains two large cities that may be affected by ashfall (Cuernavaca, ~280,000 population and Cuautla ~111,000 population); parts of the latter city lie within the paths of debris avalanches and flows (Siebe et al., 1995a). To the west of the volcano, about 1.5 to 2% of the densely populated State of Mexico (~13.1 million) may also be vulnerable to direct effects of a major eruption.

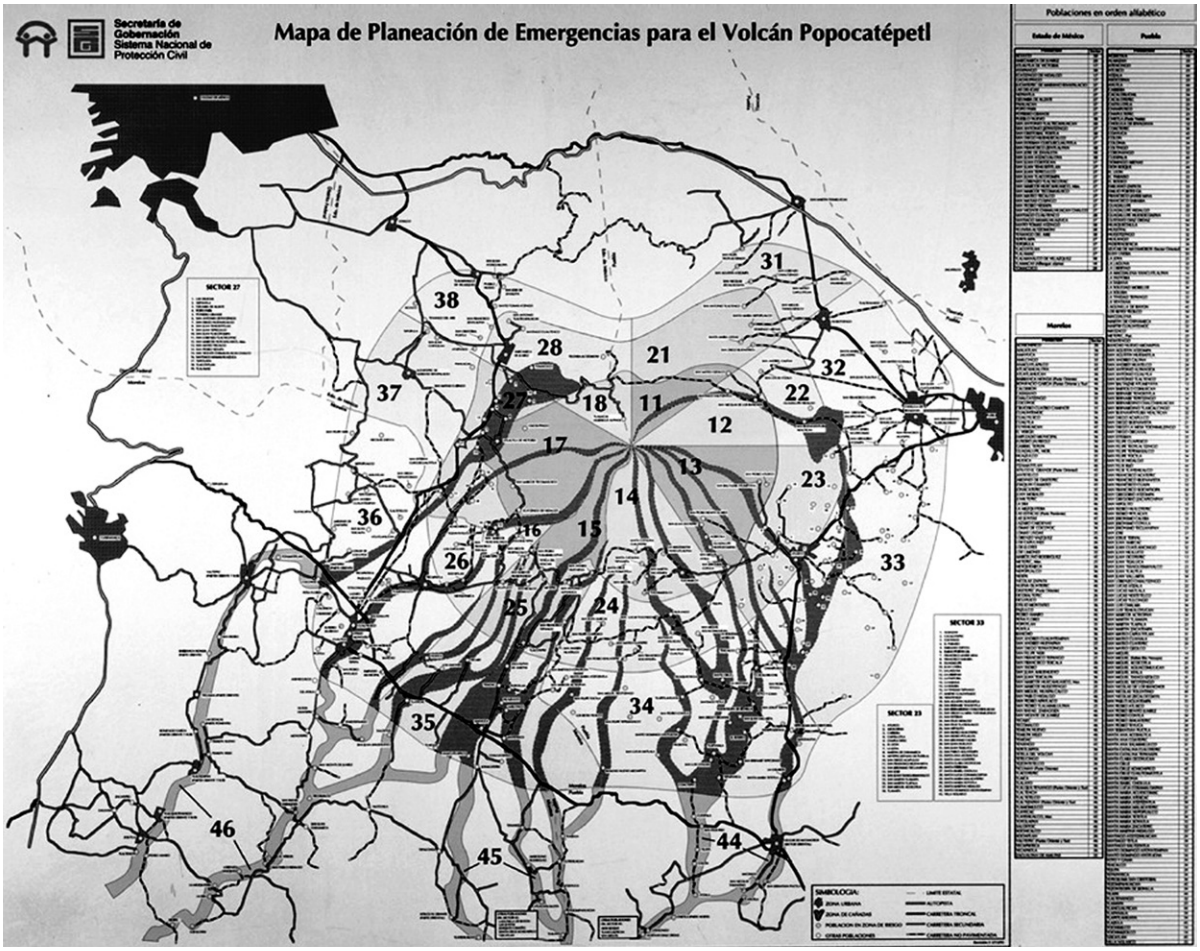


Fig. 2. Map for the emergency management of Popocatépetl. The listings show the towns located in hazardous areas. The three concentric regions defined in the Volcanic Hazards Map of Popocatépetl (Macías et al., 1995a) are divided into sectors. The first digit in each sector defines the level of hazard (1 is closest and higher exposure). The second digit defines the azimuthal position. Although vulnerable towns are indicated, their vulnerability is not specified.

In summary, ashfall hazards from a major eruption (VEI ≥ 5) may affect a population well over 20 million, and more proximal hazards (e.g., pyroclastic and debris flows) may threaten about 0.5 million. The effects of a large eruption (VEI ~ 4–5) may be very roughly estimated to be on the order of one half of those figures, and a moderate eruption (VEI ~ 3–4) may reduce the figures for people at risk by roughly the same proportion: about 5 million from ashfall hazards, and ~ 0.1–0.2 million from flowage hazards. Popocatépetl's summit crater is now partially filled by post-1994 lava-dome materials, thus posing "…a new threat to populations settled in the orange zone (intermediate hazard level) because future explosions will not be contained by the crater walls" (Macías and Siebe, 2005, p. 327).

## 2. Frequency and magnitude of Popocatépetl's eruptions

Knowledge of the frequency and magnitude of eruptions for a given volcano constitutes an essential component in making an assessment of its potential hazards and the probabilities for their recurrence within a given time interval. From the published chronology of recent eruptions (De la Cruz-Reyna et al., 1995), we have constructed Table 1 to show the distribution of the sizes of Popocatépetl's eruptions chronicled during the historical period. Inspection of the table indicates that, in an interval of 500 yr (between 1500 and 2000), 13 eruptions with VEI = 2, and 3 eruptions with VEI = 3 have been reported, resulting in rates of occurrence for each of these of magnitudes of 13/500 and 3/500, respectively. Similarly, published data for prehistoric eruptions of Popocatépetl (e.g., Macías et al., 1995b; Siebe et al., 1995b, 1996; Siebe and Macías, 2004) show that eruptions in the VEI 4 range occur at a rate of about 2 per 1000 yr, and very large eruptions in the VEI 5 range occur at a rate of 10 in 15,000 yr. The few even larger eruptions reported at Popocatépetl, perhaps approaching magnitude VEI ~ 6, may have a rate on the order of 10 in 40,000 yr. Table 2 summarizes the frequency and size distribution for known eruptions, prehistoric and historical, for Popocatépetl Volcano.

Table 2 suggests that there is a logarithmic relationship between the rates of occurrence and the VEI magnitudes (De la Cruz-Reyna, 1991). This may be clearly appreciated in Fig. 3, where the results of Table 2 are compared with the line

$$\log\lambda_\mathrm{i} = a\mathrm{VEI}_\mathrm{i} + c \tag{1}$$

where $\lambda_\mathrm{i}$ is the rate of occurrence of eruptions per year in the magnitude class $\mathrm{VEI}_\mathrm{i}$, and $a$ and $c$ are constants. For Popocatépetl, $a = -0.530$ and $c = -0.524$.

Table 2
Mean rates of occurrence of explosive eruptions of Popocatépetl Volcano for each VEI class from both historical and geological data

| | VEI | Mean occurrence rate (er/yr) |
|---|---|---|
| Historical | 2 | $\lambda_2 = 13/500$ |
| | 3 | $\lambda_3 = 3/500$ |
| Prehistoric | 4 | $\lambda_4 = 2/1000$ |
| | 5 | $\lambda_5 = 10/15,000$ |
| | 6 | $\lambda_6 = 10/40,000$ |

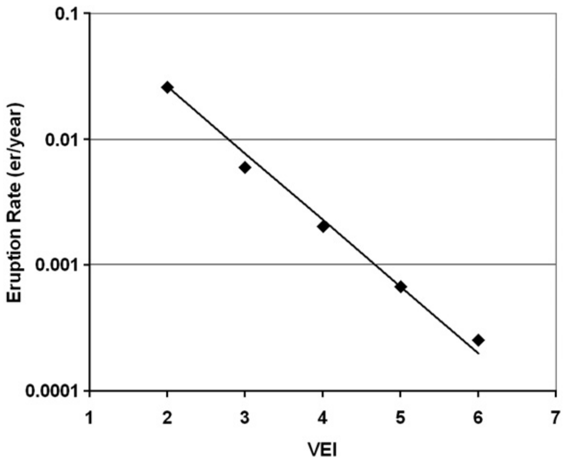


Fig. 3. The estimated eruption rates of Popocatépetl Volcano as a function of the VEI magnitudes. Rates for the high-end of VEI values were obtained from available data of prehistoric eruptions, while rates of the low-magnitude range were calculated from historical data. See Table 2.

The relatively good fit of the rate of occurrence estimates and a straight line suggests that the overall eruption rate of the volcano has varied little over a long time and that the time distribution of eruptions of different magnitudes has probably remained stationary since the Holocene and earlier.

A sequence of volcanic eruptions in any given VEI class may be represented as a Bernoulli process. This means that a succession of time intervals (say years), can be considered as a sequence of trials that may or may not include an eruption (De la Cruz-Reyna, 1996; De la Cruz-Reyna and Carrasco-Núñez, 2002). Given a probability of success $p$ (and a probability of non-occurrence $1-p$) in a stationary process, the number of successes in a given number of $n$ Bernoulli trials is described by the Binomial distribution:

$$B(n,x) = C_x p^x (1-p)^{n-x}, \tag{2}$$

where $B(n,x)$ is the probability of $x$ occurrences in $n$ trials, ${}_nC_x$ is the number of combinations of $n$ taken $x$ at a time.

Assuming that the Bernoulli process describing the eruptive sequence of Popocatépetl Volcano is stationary (a non-stationary process requires a different procedure), an approximate estimate of the probability of occurrence of future eruptions can be obtained from the mean occurrence rates (Table 2) using elementary probability computations. As this probability is a function of time (i.e., of the number of time intervals), we have used a period of 20 years, because it is a convenient interval on a human time scale for planning and development. Thus, the probability that no eruptions occur in 20 years is:

$$B_\mathrm{vei}(20,\, x=0) = {}_{20}C_0\; p^0_\mathrm{vei}(1-p_\mathrm{vei})^{20}, \tag{3}$$

and $\mathrm{Pr}_\mathrm{vei}(20) = 1 - B_\mathrm{vei}(20, x=0)$ is the probability that at least one eruption in the magnitude class *VEI* occurs in any 20-year interval. Table 3 shows the binomial probabilities of at least one eruption occurring for each VEI category in any 20-year

Table 3
Binomial probabilities of at least one eruption in the corresponding VEI class at Popocatépetl Volcano within any 20-year interval

| VEI | $Pr_{vei}(20)$ |
|---|---|
| 2 | 0.410 |
| 3 | 0.113 |
| 4 | 0.039 |
| 5 | 0.013 |
| 6 | 0.005 |

interval, assuming that Popocatépetl Volcano maintains a stationary eruptive sequence. If new geologic or historical evidence shows that the eruptive sequence of Popocatépetl is non-stationary, and the way the eruptive rates change may be estimated from such evidence, Bayesian methods provide a tool to calculate new probabilities at the light of the available data (De la Cruz-Reyna, 1996). However, in the present case, the following order-of-magnitude arguments may be valid.

The probabilities of occurrence of different eruption sizes at Popocatépetl vary over two orders of magnitude (Table 3). Ashfall hazard for the more distant, densely populated settlements related to explosive eruptions in the high-end magnitudes (VEI > 4), has to be adjusted by the probabilities of wind conditions moving the ash clouds in their directions at the time of an eruption. This additional consideration may further reduce the probability of heavy ashfall for such more-distant populations by another order of magnitude.

Despite the limitations of the probability methods discussed above, they nonetheless provide some constraints for making forecasts of the possible eruptive behavior at Popocatépetl or any other potentially active volcano. These constraints represent important decision factors for the responsible authorities, particularly if they are expressed as dissimilar scenarios' probabilities. 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. Refined probabilities should aid the management of an ongoing volcanic crisis by helping to answer critical questions facing scientists, civil authorities, and the affected public, such as: What is the likelihood in the near term of an explosive eruption occurring that would be much more powerful, hence more dangerous, than the current eruption and previous historical eruptions, or why the limited resources of the civil authorities are being spent disproportionately for protection of small towns around the volcano rather than of the large cities?

## 3. The perception of risk

Effectiveness of response in reducing volcano risk and the *perception* of risk are closely related. The way that the public, authorities, media and scientists respond to a given threatening phenomenon strongly depends of the way they perceive the risk. Ideally, an optimum societal response should be obtained when those components of the social network share the same perception of risk. However, this is much easier said than done. For the Popocatépetl volcanic crisis, attempts to foster a reasonably uniform perception of the risk in a huge and diverse population have proved to be very difficult. In a large part, this difficulty stems from the fact that populations at different areas around the volcano may have quite different degrees of exposure to a variety of volcanic manifestations with probabilities of their occurrence varying from two to three orders of magnitude, as discussed above.

The problem starts with the definition of *risk* itself. Several definitions have been widely used in the volcano-hazards literature (e.g., Fournier d'Albe, 1979; Newhall, 1982, 2000; Tilling, 1989; Blong, 2000). Currently, we have (*in Mexico*) tried to use a practical form of the original risk formulas, appropriate for making these concepts more accessible to the decision-makers. This proposed formula for defining the risk is:

$$R = H^*(V - P) \tag{4}$$

where $H$, the hazard is the probability that a specific volcanic manifestation or phenomenon occurs in a given area, within a given interval of time; $V$, the vulnerability, is the expected percentage loss of the exposed value should the hazardous manifestation occur (i.e., *probability of loss*). The symbol * is the product of every pair of possible known hazardous manifestation and component of vulnerability that may be realistically considered. $P$ may be defined as the "preparation," here referring to the series of measures to reduce the vulnerability. The risk is, therefore, the probability of losing a certain percent of the value of a given region over a given time interval caused by the possible occurrence of a particular volcanic manifestation. Thus, risk is reduced as proper measures to reduce vulnerability that are implemented.

Although a risk map following the above concepts for Popocatépetl Volcano has not yet been produced, the map in Fig. 2, showing the volcanic hazards and the threatened settlements perhaps might be considered as a forerunner of such a map, as part of a long-range project (*National Atlas of Natural Risks: Integral Information System*) of Mexico's Sistema Nacional de Protección Civil (National System of Civil Protection) with a dynamic GIS.

## 4. Risk-management approach and procedures

Any analysis of the approach and procedures in the risk management of the 1994–present Popocatépetl volcanic crisis must be done within the context of the local culture background, as well as the structure of the national and local governmental agencies involved. Some non-governmental organizations (NGOs) also may play a role.

The National Civil Protection System of México (SINAPROC) was created after the great disaster caused by the magnitude 8.1 earthquake of September 19, 1985. According to the law, the SINAPROC consists of a set of organizations, structures, functional relationships, methods, and procedures established by all the state bodies at all levels of government, including the involvement of NGOs, voluntary or private, as appropriate. The principal objective of SINAPROC is to execute coordinated actions directed for the protection, prevention, help and recovery of people and communities from hazards associated with natural or man-made phenomena; in so doing, SINAPROC also promotes the protection of property, productive infrastructure, and environment. Among the main functions of the SINAPROC stipulated in the law, is to promote the people's education for self-protection, and for active participation in the risk-management system.

The executive Coordination of the SINAPROC at the federal level is in the Ministry of the Interior (Secretaría de Gobernación) at a level equivalent to an undersecretary of state. The Coordination is supported by two main bodies: The National Direction of Civil Protection, an operational body in charge of implementing the preventive, and relief actions, and the National Center for Disaster Prevention (CENAPRED), a technical body whose objectives are to promote the applications of technology for the prevention and mitigation of disasters, to train and inform professionals and technicians on these subjects, and to disseminate the necessary information for preparedness and self-protection to all the people exposed to a hazardous phenomena. CENAPRED was created in September 19, 1988, with substantial technical and generous economical support from the government of Japan. Initially, CENAPRED began its scientific and technical activities with personnel commissioned from the National Autonomous University of Mexico (UNAM), which also provided the land for the construction of the CENAPRED building, which was financed by the government of Japan. The Mexican Ministry of Interior provides the funds for the operation of CENAPRED.

CENAPRED also acts as an active interface between the operative, decision-making authorities of the SINAPROC, and the academic scientific community. CENAPRED utilizes five advisory committees on topics relevant for disaster prevention, composed of prominent, experienced Mexican scientists in the areas of earth sciences, hydro-meteorological sciences, social sciences, chemical and industrial hazards, and health (sanitary) sciences. Some of these Committees form ad-hoc sub-committees, as is the case of the Advisory Committee for Popocatépetl Volcano, on which several international volcanologists—especially from the U.S. Geological Survey (USGS)—actively participated. This advisory committee will be herein referred as the *Scientific Committee* (SC). Among other specific functions of CENAPRED is the monitoring of Popocatépetl Volcano.

## 5. Popocatépetl's reawakening and eruption: scientific and public responses

As a case history, we highlight here selected aspects of the reawakening and ensuing eruption at Popocatépetl, to illustrate some of the scientific and public responses undertaken to deal with a threatening volcano in a densely populated region. For more information about the 1994–present eruptive activity, including chronological summaries, the interested reader is directed to a comprehensive hardcopy publication (CENAPRED-UNAM, 1995) and the following websites of the CENAPRED and the Global Volcanism Program of the Smithsonian Institution: <http://www.volcano.si.edu/world/volcano.cfm?vnum=1401-09=&VErupt=Y&VSources=Y&VRep=Y&VWeekly=Y&volpage=var> and <http://www.cenapred.unam.mx/popo/resumen9497.html>.

After nearly 70 years of quiescence, an early sign of volcano unrest at Popocatépetl was noted in late January, 1986, by the Mountain Climbers Group of UNAM reporting increased fumarolic activity within the summit crater (SEAN, 1986). In September 1989, the Instituto de Geofísica (Institute of Geophysics) of UNAM installed the first telemetered seismic station dedicated to monitoring the activity of Popocatépetl Volcano at Tlamacas (~4000 m a.s.l.) on the volcano's northern slope, 4.8 km north of the crater. Another station (Altzomoni), located about 12 km N of the Popocatépetl summit, had existed since 1987 as part of the Valley of Mexico Network, but its greater distance to the volcano and relatively low-gain made detection of the volcano's low-level activity difficult. A small geodetic network was established on the northern flank of the volcano in February, 1992.

Although precursory volcanotectonic seismic activity probably began in 1990, stronger manifestations signaling the possible reawakening of the volcano appeared in 1993, as expressed by a significant rise in both fumarolic and seismic activity. Using correlation spectrometry (COSPEC), occasional airborne measurements of $SO_2$ emission from the summit were begun in February 1994. By October 1994, volcano unrest increased markedly, and an "Emergency Committee" was formed by Federal and state authorities, composed of scientists from UNAM, other universities, and CENAPRED. This committee's charter was to augment volcano monitoring and to evaluate potential hazards and risk, should the increased unrest lead to eruption. Two additional telemetric monitoring stations were installed: "Chiquipixtle," about 4 km SW of the crater in October 1994, and "Colibrí," about 7 km SE of the crater in November 1994 (Quaas et al., 1995). The Committee's first risk assessments were based on the hazards map of Boudal and Robin (1989).

The intensifying precursory activity at Popocatépetl culminated in the first hours (0154, local time) of December 21, 1994, with a series of moderately large explosions at the crater. These produced emissions of ash, which fell on several towns to the east and northeast of the volcano, including the city of Puebla causing sudden and considerable distress for the officials and the public. At that time, little information was available about geophysical, geochemical and petrological parameters that could define more precisely the nature of the ongoing activity. Decision-making had to be done with scant knowledge under acutely adverse conditions:

a) The ash-bearing explosions occurred suddenly with no immediate unambiguous precursors. Previous visible activity had been of hydrothermal nature: white-colored steaming fumaroles; heating and evaporation of the small crater lake.
b) Dedicated real-time monitoring of the volcano was limited to a single short-period, vertical seismic station until late 1994, and to 3 similar stations until mid-1995. However, other stations of the Valley of Mexico seismic network and the National Seismological Service provided some useful data.

c) No emergency plan or alert code existed for Popocatépetl Volcano at that time.
d) The ash-producing explosions occurred at the beginning of the Christmas holiday season, when the immediate availability of scientists and some authorities was reduced.
e) The north and northwestern flanks of the volcano summit were capped by glaciers. The available estimates for the area of the glaciers at that time were 0.45 $km^2$ for the Ventorrillo Glacier, and 0.16 $km^2$ for the NW glacier, with an estimated average thickness probably exceeding 10 to 15 m (Delgado, 1993; Delgado and Brugman, 1995).

With daylight, several helicopter flights showed (for the first time in about 70 years) a dense column of ash rising from the crater; the column tended to gain height and volume as the day progressed. Noon of same day, in a meeting of the Emergency Committee, headed by the Minister of the Interior, the various scenarios of possible outcomes of the ongoing activity were analyzed. Particular attention was paid to a Nevado del Ruiz (Colombia) 1985 scenario. Telephone and faxed consultations with specialists of the USGS (T. Pierson, written communication) emphasized that rapid melting of several meters of the ice caps by pyroclastic flows might produce lahars large enough to reach the nearest towns in the NW sector or the volcano in few tens of minutes. Even though the eruption had not yet produced any pyroclastic flows, as a prudent preventive measure, a decision was made to evacuate in the afternoon some of the most vulnerable nearby towns located along the most likely paths of pyroclastic flows and lahars. The total number of evacuees was nearly 25,000, dwelling in 23 small towns, and a number self-evacuated. Authorities established a zone of restricted access, delimited by a 12-km radius from the volcano summit. About a week later, the eruption still had not produced pyroclastic activity and the activity decreased; low-intensity ash emissions became less frequent and shorter in duration, and were determined to be of phreatic origin. The evacuation order was lifted and people returned to their homes.

Following Popocatépetl's initial outburst, low-level activity persisted through 1995 into early 1996, permitting expansion of the monitoring network operated by CENAPRED (which included the Tlamacas station). The expansion was accomplished with the help of the USGS, which provided much of the equipment for the monitoring network as well as assistance in the assessment of hazards. Two additional seismometers and three tiltmeters were installed around the volcano during the last days of December 1994 and early 1995. Also, during this time an international geological team was quickly assembled to make, using the limited information then available, a Volcanic Hazards Map for Popocatépetl (Macías et al., 1995a); this map was delivered to CENAPRED on February 17.

In the spring of 1996, the volcano again showed increasing activity. By late March 1996, a fresh lava dome was observed growing on the floor of the crater, marking the first appearance of juvenile lava (Siebe and Macías, 2004). The expanded monitoring system now allowed a much better understanding of the ongoing processes. Although the intensity of the eruption in March 1996 was similar to the levels reached in December 1994, no evacuations were recommended by the scientists at that time. The first dome-destruction explosion occurred on April 30, 1996, followed by a series of at least 26 dome growth-explosive and destruction episodes that lasted until July 2005, when the last dome (as of this writing, November 15, 2005) was extruded. The April 30, 1996 explosion caused the only reported victims directly related to the Popocatépetl eruptive activity: five climbers had climbed to the summit crater and were hit by hot explosion debris during their descent, a few hundreds of meters downslope from the crater.

Between 1996 and 1999, episodes of dome emplacement followed by increasingly strong dome-destruction explosions generated an extensive concern for the populations living within nearly 100 km of the volcano. One particular episode substantially disrupted daily life and contributed much to the distress of people and authorities. On June 30, 1997, a particularly strong succession of explosions obliterated one of the largest domes emplaced to that date and produced a 13-km high ash plume. Drifting ash from this plume, driven by fairly strong winds from the southeast, generated a mild, yet conspicuous ashfall on the metropolitan areas of Mexico City. The international airport of Mexico City, which moves over 20 million passengers per year, had to shut down for about 12 h until the runways were cleaned of ash. The management of this event caused some confusion: While members of the Scientific Committee (SC) regarded it as the largest eruption to that date since the beginning of the eruptive episode in 1994 and suggested a maximum alert condition, the perception of federal and state authorities did not coincide. While state and municipal officials were ready to begin a preventive evacuation of the same towns that were evacuated in 1994, the federal officials decided not to order an evacuation. The need of a clearer alert code became evident. During the next two days, small lahars reached the lowermost parts of Santiago Xalizintla, one of the towns evacuated in 1994. While they caused only minor damage to only one small house, these lahars, together with the ashfall still fresh in the public mind, perhaps 10 million people suddenly become aware that they were living within the reach of potentially dangerous volcanic phenomena. However, the combination of strong explosions and southeasterly winds did not materialize frequently; with reduced activity in the ensuing months, the abruptly enhanced awareness of volcano hazards in the heavily populated areas slowly faded away.

Explosions ejecting large amounts of incandescent debris onto the flanks of the volcanic cone were common in late 1998 and sporadically through 1999, which was characterized by significant volcanotectonic activity at Popocatépetl, as well as two damaging regional earthquakes. On June 16, 1999, a Ms-6.7 intraplate earthquake struck the border area of Puebla–Oaxaca and caused widespread damage; on October 1, a Ms-7.4 shock affected the coastal zone of Oaxaca.

The initial months of 2000 were relatively calm. The dome emplacement and destruction continued but at lower rates (only one small dome grew in February). During August–September 2000, the occurrence of relatively large volcanotectonic (VT) events marked the beginning of a new episode of increased volcanic activity. Harmonic tremors, VT earthquakes, stronger exhalations and other monitored parameters showed an increase in the subsurface activity of Popocatépetl. In mid-September, 2000, a flight over the crater revealed a new small lava dome growing slowly in the crater floor. The explosivity of exhalations increased through October, ejecting incandescent debris onto the flanks and generating plumes up to 6 km above the summit. In November, the internal activity further increased. Energetic VT activity included events of magnitude 3 and 3.1, before declining in late November. On December 2, a low-intensity but long exhalation (90 min) marked the onset of a higher level of activity. On December 6, a swarm of six VT events was followed by harmonic tremor of very large amplitude (largest to that date) and then by new VT swarms on December 8 and 9.

On December 12, the exhalation activity surged to 200/day, with many of the exhalations producing ash columns 5–6 km over the summit. During the night, incandescence could be seen within the crater, along with some minor ejections of hot debris. On December 15, low-frequency, very high-amplitude harmonic tremors were detected again. That day, at 1404 local time, the low-frequency harmonic tremor energy grew to an awesome level, saturating all the 1-second seismic stations, even the farther ones. This tremor was felt by people in towns 12 to 14 km from the summit. The national seismic network detected the tremor in stations located 150 km away. This unusually strong tremor signal lasted 10 h, before stopping abruptly in the morning of December 16. Sixteen hours later, the tremor signal reappeared, growing again to saturation level for all the dedicated volcano seismic-monitoring stations. This new episode of tremor lasted 9.5h, during which several pens of the seismometer drums were damaged while registering the tremor signals. For the first time since they were installed in 1995, the electronic tiltmeters detected variations associated with the tremor, as oscillations in tilt of amplitudes up to 100–200 μrad. COSPEC measurements, which had averaged 5000 t/day during previous years, reached values over 50,000 t/day after December 13, and even higher on December 19 (Valdés et al., 2001). The RSAM data describe well the nature of this event. During the 25 hours of large-amplitude harmonic tremor, the seismic energy release exceeded the seismic energy released during 1997, the year with the largest events to that date. The succession of tremor episodes appeared to be following a time-predictable load-and-discharge process (Carlos Valdés personal communication; Valdés et al., 2001) of the type described by Shimazaki and Nakata (1980). Because of these well-documented observations, it was possible to make a forecast for the next episode, which ultimately proved to be the largest to date. Based on this forecast, a specially organized decision-making group headed by the secretary of state, decided to carry out a preventive evacuation of the same areas that were evacuated in December 1994, and some other vulnerable areas. Analysis of aerial photographs obtained on December 16, suggested this activity was caused by the growth of a large dome at a very high rate. The magma production rate was estimated to be between 180 and 200 $m^3/s$. This was about two orders of magnitude greater than any rate observed before in Popocatépetl.

In the preceding paragraphs, we purposely have provided more detail in summarizing the volcano-monitoring data and their interpretation. The reason is simple: As the eruptive sequence progressed, the monitoring networks and data collected improved greatly in quantity and quality, such that the scientists became incrementally more knowledgeable and comfortable in analyzing and interpreting the data. The increased capability and confidence would play a critical role in the scientific and public responses in dealing with dramatic escalation of activity during December 2000.

Unlike the situation of June 30, 1997, an improved alert code (described in the next section) permitted a more unified perception of the level of hazard and of the nature of the scientific forecast. This translated into a consensus among officials at all levels of government, and a preventive evacuation was decided on the basis of the SC forecast about 24 h before the peak of activity.

Fortunately, the eruption was not as powerful as suggested by the strength of tremor signals, and while no volcanic products damaged any town of infrastructure, thousands of evacuees could watch the striking view of showers of hot debris falling on the volcano flanks from the safety of their shelters.

## 6. The “Volcanic Traffic Light” Alert System and the communication protocols

In the previous sections, we presented a condensed, selective description of the activity of Popocatépetl, its evolution, the probabilities of eruptions of different sizes, and the very different degrees of exposure and vulnerability of a large population around the volcano. Here, we discuss the alert mechanisms that were developed within that context, attempting to obtain a uniform perception of the changing risks among scientists, authorities, media and the general public.

We may consider the progress of the volcanic activity, which furnishes context for the development of the alert codes, as consisting of several steps:

a) *The build-up to eruption (1993–1994)*. Not surprisingly, given the long dormancy of the volcano before 1994, the level of awareness at that time was low and confined to the scientific community. Analysis of the previous activity prompted the installation of an incipient monitoring system of telemetric dedicated stations.
b) *Initial activity (December 1994)*. The sudden appearance of conspicuous ash columns and ashfalls immediately grabbed public attention and caused the hurried (within hours) formation of an Emergency Committee. Lacking a fully staffed scientific committee (because of the holiday season and the rapid development of events), and considering the possibility of Nevado del Ruiz scenarios derived from the increasing eruptive activity, federal government authorities quickly (same day) ordered a partial preventive evacuation of the towns considered most vulnerable to pyroclastic flows and lahars. Elucidation of the phreatic character of the initial stage of the eruption and decrease of the ash production prompted the end of the evacuation.

c) *Assessment stage (most of 1995)*. The reduced, but continuing, activity of Popocatépetl prompted the formation of an ad-hoc Scientific Committee (SC) composed of Mexican (mostly from UNAM, CENAPRED, Puebla University and other institutes) and foreign scientist (mostly from the USGS, and Japan). In February, a group of geologists (Macías et al., 1995a) was quickly assembled to produce an updated hazards map of the volcano. Other groups were organized to expand the monitoring of the volcano: seismic, geodetic, geochemical (mostly analysis of water and ash samples), and gas production (COSPEC traverses). All of these groups were supported by the technical staff of CENAPRED. An additional group, composed of scientists and authorities, started working on an alert code and communications protocol. Only the results of the alert-code group are discussed below.
d) *Evolution stage (1996–2003)*. The characteristic mode of the eruptive activity during this period was the succession of dome growth and explosive destruction. However, the nature of this process changed significantly with time, particularly the precursors for individual episodes. Signals that were clearly recognized as precursors of anticipated new domes emplacements, or of dome-destruction explosions in the earlier episodes began to change significantly, and eventually the expected dome growth or explosion event did not match the precursory signals. Instead, new and different seismic signatures were recognized, and much of the time of the SC was focused on the continuously evolving signals and on how these could be interpreted and correlated with the visible eruptive activity.

Initial efforts to design an alert code in 1995 included a compilation and analysis of the existing alert codes for other volcanoes of the world, departing from the basic UNDRO-UNESCO (1985) basic booklet. Following this analysis, a four-color code was first proposed: from green indicating a calm volcano to red indicating hazardous volcanic conditions with two intermediate conditions (yellow and orange). However, as discussed below, some difficulties were found with this type of code. Also, members of the SC found it difficult to agree on the significance and interpretation of the observed changes or precursors. Sometimes, manifestations that some members considered a significant precursor, were deemed insignificant and (or) irrelevant by specialists in other disciplines. During the evolution stage of the eruption, it became increasingly clear that it was very difficult to assign a level of alert depending only on the observed precursors.

At the same time, the decision-making authorities found it increasingly difficult to understand the explanations of the SC: the terminology and jargon used to describe the signals detected by the monitoring devices and the samples of eruptive products were unfamiliar, and it was difficult to understand the disagreements among the scientists that sometimes resulted from different ideas about the evolution of the eruption and the presumed precursors. Such uncertainties and difficulties were recognized by the small percent of the public that was aware of this poorly-disseminated alert code. Several private, non-governmental organizations, and individuals sent to CENAPRED their own proposals for different alert codes, varying from 4 to 10 levels of alert, and many diverse interpretations of the criteria for assigning the level in terms of the activity of the volcano. It should be noted, however, similar problems also frustrate many other volcano observatories and scientific institutions dedicated to monitoring studies.

In any case, during the middle of the evolution stage of the eruption, three things became clear:

1. Decision-making authorities found it difficult to understand the explanations of the SC when they contained abundant scientific terminology and untranslated monitoring results. However, they were more receptive when the precursors were translated into the most probable scenarios of impact developed by consensus of the SC members. *(This means that instead of telling them that the increased boron levels detected in some water springs, followed by low-frequency tremor signals might precede pyroclastic flows which could generate lahars, it was much clearer to tell them that there was an increased probability that a destructive flow of mud may reach Santiago Xalizintla about 15 min after a large explosion).*
2. The most vulnerable part of the population found it equally difficult to understand the differences between the four levels of alert, particularly between yellow and orange, in terms of actual risk for their home or village.
3. It is extremely difficult to communicate and to attain a uniform level of perception and understanding of the risk for the large populations ($10^5$–$10^6$) surrounding the volcano.

The idea of the “Volcanic Traffic Light” alert system (VTLAS) finally emerged from the above-discussed difficulties encountered in attempting the initial four-color-alert system. This VTLAS system (Table 4) idea is based on two basic concepts:

a) The level of activity of the volcano is defined by the SC. One of its main functions is then to translate the observed activity in terms of the most probable scenarios, describing them in specific terms, including time scales, names of threatened towns, etc. In general terms, these sets of scenarios may be grouped according to seven levels (*phases* within each of the Traffic light colors: two for green, three for yellow and two for red).
b) The Civil Protection authorities (CPA) translate these criteria into an alert level of the population (not of the volcano), in three levels that leave no room for uncertainty: green: everything is fine. Yellow: you must be aware of the hazard and pay attention to any announcement. Red: you must leave the area according to the instructions given by the authorities.

The SC sessions also became more facile and efficient when the discussions focused on the likelihood of various scenarios. It was easier to reach consensus on this than on explaining the nature of the observations. This does not mean that scientific

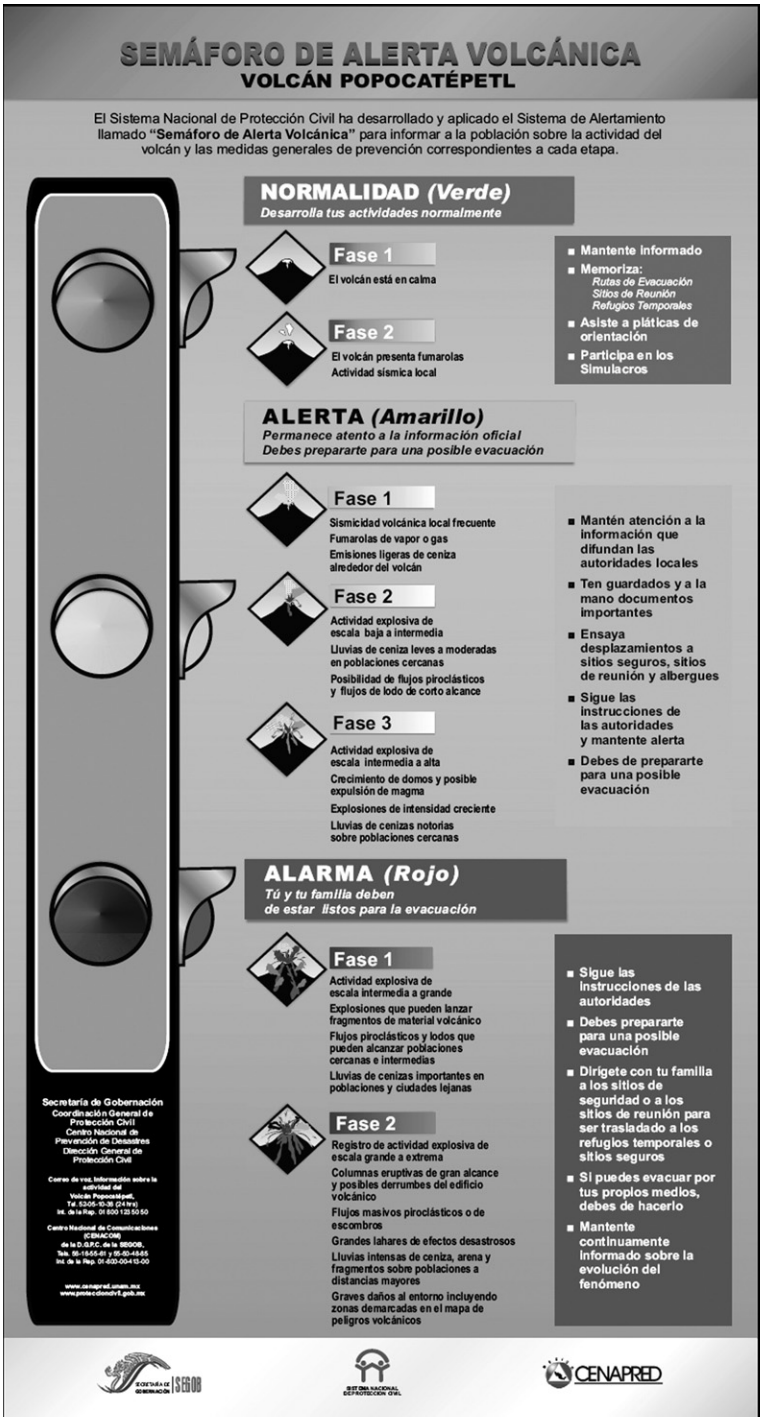
Table 4
The levels of the "Volcano Traffic Light Alert System" (VTLAS). The column of the left reflects the state of the volcano as interpreted by the Scientific Committee. The second column shows the most probable general scenarios, based on SC's interpretations of volcano-monitoring data and visual observations visible eruptive activity. The third column shows the general actions recommended to the Civil Protection (CP) authorities, and the fourth column reflects the state of alert for the populations at risk. Specific actions for the CP authorities are described in the "procedure manuals" which have proven to be one of the most difficult parts of the plan to develop. See Fig. 4 for an example of how the alert level is indicated for the general public by analogy to traffic signal lights

| Alert level: communication SC-SINAPROC | Expected scenarios | Actions recommended to SINAPROC | Alert level of the public. Recommended actions |
|---|---|---|---|
| Green. Phase 1 | – The volcano is quiet<br>– Sporadic seismic signals | – Develop preparedness plans<br>– Promote education programs<br>– Maintenance of monitoring devices | Green. Normality<br>– Keep informed<br>– Learn about volcanic phenomena |
| Green. Phase 2 | – Low-level seismic activity recorded only at nearest stations | – Increase monitoring | – Memorize signals: |
| | – Some fumarolic activity | – Promote more frequent meetings of the SC. | — Evacuation routes |
| | – Minor changes in temperature of fumaroles | – Increased communication between SC and SINAPROC | — Meeting sites |
| | – Minor changes in the composition of spring waters, that do not affect significantly its quality for agricultural and public use | – Review of emergency plans | — Shelters |
| | | – Increase dissemination of volcano information to the public | – Attend information meetings |
| | | | – Join exercises and drills<br>– Promote relocation of vulnerable property |
| Yellow. Phase 1 | – Increase of low-level local seismicity | –Promote more frequent meetings of the SC and joint meetings with SINAPROC. | Yellow. Alert |
| | – Gas or steam fumaroles, and/or light ash emissions | –Recommend specific studies on the volcano. | – Keep well informed. Pay special attention to official spots |
| | – These manifestations may cause acidification of meteoric rain and light ashfalls on towns surrounding the volcano. Some of them may pose a slight threat to air traffic | –Check availability of staff, equipment and vehicles required for evacuations. | – Keep valuable documents in an easy to carry envelope |
| | | –Ask the SC to define criteria limiting access to the volcano | – Try the evacuation routes to meeting sites, security areas and shelters |
| | | –Issue warnings to the aircraft controllers. | – Listen and obey instructions from authorities and remain alert |
| Yellow. Phase 2 | –Low to intermediate eruptive activity (VEI $\leq 2$) | –Communicate the change of alert level to authorities in the three levels of government: municipal, state and federal, and to all involved officials. | – Be prepared for a possible evacuation |
| | –This level of activity may produce moderate explosions ejecting debris around the volcano crater. | –Keep shifts of emergency staff. | |
| | –The explosions may eject ash and produce light to moderate ashfalls on nearby towns, and farther cities if wind is strong. | –Increase area of restricted access around the volcano according to the recommendations of the SC. | |
| | –The ash in the air may pose an important threat to aircrafts. | –Issue warnings to the air navigation systems | |
| | –Low-level pyroclastic flows and mud flows (lahars) may develop without reaching populated areas. | | |
| Yellow. Phase 3 | –Phreatic or magmatic eruptive activity of intermediate to high explosivity (VEI 2–3) | –Keep the public and the media well informed about the situation and the measures taken. | |
| | –Growth of lava domes and increased probability of magma ejection. | –Prepare staff and equipment for shelter operation. | |
| | –Possibility of explosions of increasing intensity ejecting hot debris to significant distances (several kilometers). | –Implement specific measures in most vulnerable areas. | |
| | –Conspicuous ashfall on towns and cities. | –Start preventive measures against ash and debris falls and against lahars in highly vulnerable areas. (this may include some evacuations). | |

Table 4 (*continued*)

| Alert level: communication SC-SINAPROC | Expected scenarios | Actions recommended to SINAPROC | Alert level of the public. Recommended actions |
|---|---|---|---|
| | –Possibility of larger pyroclastic flows and lahars, not reaching populated areas. | –Further increase of restricted area around the volcano | |
| | –Increased risk to aircrafts and light effects on airports. | –Alert all systems of air traffic and navigation. | |
| Red. Phase 1 | – Intermediate to large explosive eruptions (VEI 3–4) producing eruptive columns capable to reach the stratosphere | – Selective evacuations according to criteria of the SC defined by the development and intensity of the eruption | Red. Alarm |
| | | – Inform and promote about auto-evacuations in selected areas | – Keep well informed. Pay full attention to official spots and obey instructions |
| | – The explosions may eject considerable amounts of ash and fragments reaching the nearest towns | – Implement specific preventive measures against ash and fragment falls in the regions near the volcano defined by the SC | – Take with you valuable documents in an easy to carry envelope and go to meeting sites, security areas and shelters according to the instructions of the Civil Protection officials |
| | – Production of large-scale pyroclastic flows and mud flows capable to reach nearest towns and beyond | – Implement specific preventive measures against pyroclastic flows, surges and lahars in the regions defined by the SC | – If you can leave a hazardous area by yourself, do not hesitate |
| | – Important ashfalls in towns at intermediate distances capable to produce roof collapses. Significant ashfalls in large cities around the volcano | – Implement preventive measures against moderate to intermediate ashfalls in metropolitan areas of proximal large cities | – Keep informed about the evolution of the eruption |
| | | – Implement emergency plans to protect and maintain communication lines and water and food supply | |
| | – Serious threat to aircrafts over large distances. Serious effects on airports | – Nation-wide and international warnings to all aircrafts and airports | |
| Red. Phase 2 | – Large to extreme eruption (VEI>4) | – Extensive evacuations according to criteria of the SC defined by the evolution and intensity of the eruption | |
| | – Production of volcanic very large-scale clouds to the stratosphere | – Inform and promote about auto-evacuations over extended areas defined by the SC | |
| | – Possibility of massive sector collapse of the volcano producing extensive debris avalanches | – Implement specific preventive measures against intense ash and fragment falls in the regions defined by the SC | |
| | – Massive pyroclastic flows | – Implement specific preventive measures against massive debris flows, pyroclastic flows, surges and lahars in regions defined by the SC | |
| | – Massive lahars reaching distances beyond the extent of the Hazards Map | | |
| | – Devastation of the regions defined in the Hazard Map | – Implement preventive measures against intermediate to large ash and fragment falls in metropolitan areas of proximal large cities, including anti-panic measures for total blockage of sunlight | |
| | – Intense ashfalls and fragment fall on metropolitan areas in cities within a radius exceeding 100 km | | |
| | – Maximum threat to all aircraft nation and continent-wide | – Implement emergency plans to protect and maintain communication lines and water and food supply | |
| | – Serious threat to airports nation-wide | – Nation-wide and international warnings to all aircrafts and airports | |

discussions on the nature of the eruption among members of the SC or other involved scientists were discarded or neglected. Instead, in the assessment sessions, where high-rank government officials were frequently present, the scientific observations were briefly described but most of the discussion addressed the specific scenarios of risk. It was also agreed that the SC should as much as possible avoid making explicit recommendations involving evacuations, although this was



**SEMÁFORO DE ALERTA VOLCÁNICA**
**VOLCÁN POPOCATÉPETL**

El Sistema Nacional de Protección Civil ha desarrollado y aplicado el Sistema de Alertamiento llamado **"Semáforo de Alerta Volcánica"** para informar a la población sobre la actividad del volcán y las medidas generales de prevención correspondientes a cada etapa.

**NORMALIDAD *(Verde)***
***Desarrolla tus actividades normalmente***

**Fase 1**
El volcán está en calma

**Fase 2**
El volcán presenta fumarolas
Actividad sísmica local

- **Mantente informado**
- **Memoriza:**
  - *Rutas de Evacuación*
  - *Sitios de Reunión*
  - *Refugios Temporales*
- **Asiste a pláticas de orientación**
- **Participa en los Simulacros**

**ALERTA *(Amarillo)***
***Permanece atento a la información oficial***
***Debes prepararte para una posible evacuación***

**Fase 1**
Sismicidad volcánica local frecuente
Fumarolas de vapor o gas
Emisiones ligeras de ceniza alrededor del volcán

**Fase 2**
Actividad explosiva de escala baja a intermedia
Lluvias de ceniza leves a moderadas en poblaciones cercanas
Posibilidad de flujos piroclásticos y flujos de lodo de corto alcance

**Fase 3**
Actividad explosiva de escala intermedia a alta
Crecimiento de domos y posible expulsión de magma
Explosiones de intensidad creciente
Lluvias de cenizas notorias sobre poblaciones cercanas

- **Mantén atención a la información que difundan las autoridades locales**
- **Ten guardados y a la mano documentos importantes**
- **Ensaya desplazamientos a sitios seguros, sitios de reunión y albergues**
- **Sigue las instrucciones de las autoridades y mantente alerta**
- **Debes de prepararte para una posible evacuación**

**ALARMA *(Rojo)***
***Tú y tu familia deben de estar listos para la evacuación***

**Fase 1**
Actividad explosiva de escala intermedia a grande
Explosiones que pueden lanzar fragmentos de material volcánico
Flujos piroclásticos y lodos que pueden alcanzar poblaciones cercanas e intermedias
Lluvias de cenizas importantes en poblaciones y ciudades lejanas

**Fase 2**
Registro de actividad explosiva de escala grande a extrema
Columnas eruptivas de gran alcance y posibles derrumbes del edificio volcánico
Flujos masivos piroclásticos o de escombros
Grandes lahares de efectos desastrosos
Lluvias intensas de ceniza, arena y fragmentos sobre poblaciones a distancias mayores
Graves daños al entorno incluyendo zonas demarcadas en el mapa de peligros volcánicos

- **Sigue las instrucciones de las autoridades**
- **Debes prepararte para una posible evacuación**
- **Dirígete con tu familia a los sitios de seguridad o a los sitios de reunión para ser trasladado a los refugios temporales o sitios seguros**
- **Si puedes evacuar por tus propios medios, debes de hacerlo**
- **Mantente continuamente informado sobre la evolución del fenómeno**

**Secretaría de Gobernación**
Coordinación General de Protección Civil
Centro Nacional de Prevención de Desastres
Dirección General de Protección Civil

Correo de voz. Información sobre la actividad del Volcán Popocatépetl,

Centro Nacional de Comunicaciones (CENACOM) de la D.G.P.C. de la SEGOB,

www.cenapred.unam.mx
www.proteccioncivil.gob.mx

SEGOB
CENAPRED

Fig. 4. An example of a poster designed for public offices showing the VTLAS.

somewhat implicit in the nature of the proposed scenarios. All decisions involving preventive or reactive actions must be undertaken by the Civil Protection authorities.

The VTLAS also proved to be a great help when dealing with media. After the press became familiar with the color code, reporting the color of the Volcanic Traffic Light became as common as the weather reports. Fig. 4 shows a poster designed for government and media offices.

With use over several years, the VTLAS became more familiar and naturally adopted certain inertia, making it less mobile than it was expected during its design. Most of the time since its implementation, it has remained in yellow, and only the phases within that color have changed more frequently. Several changes from Yellow-2 to Yellow-3, related to changing precursory parameters and increased explosive activity translated mostly into the availability of evacuation transportation in the most vulnerable areas and increased readiness of the shelters. Only in two occasions the VTLAS turned red.

Fig. 5 shows a plot of the RSAM cumulative energy during the years of highest activity of Popocatépetl. RSAM is a

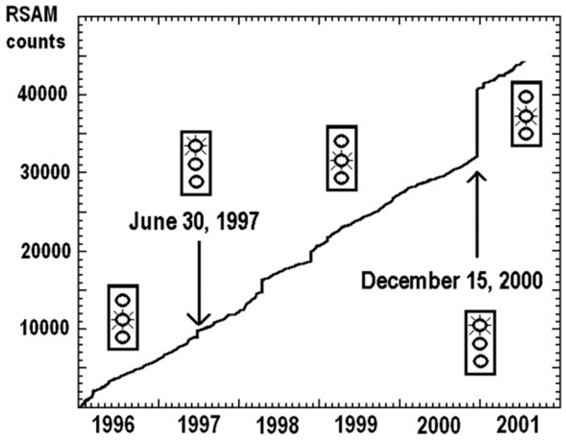


Fig. 5. The few changes of the VTLAS during the periods of highest activity. Most of the time the Traffic Light for the public has remained in yellow, reflecting the relative stability of the cumulative RSAM curve slope. For only two times were red conditions set (see text). Two of the steps in the RSAM curve mark the events of June 30, 1997 that produced ashfalls in Mexico City (but no evacuations), and December 15–19 2000 that produced the largest eruption of the episode (and a preventive evacuation). Most of the seismic energy of these steps was released by the precursory harmonic tremors; other steps in the curve were related to regional earthquakes.

real-time seismic amplitude measurement capability that continuously samples the absolute amplitude of the seismometer signals (Murray and Endo, 1989; Endo and Murray, 1991; Murray et al., 1996). From this, the cumulative seismic energy released by the volcano provides a very good representation of its level of eruptive activity.

Over the scale of years, the RSAM curve in Fig. 5 has maintained a rather uniform slope. Two steps in the line have been significant enough to change the color of the Volcanic Traffic Light. The first one on June 30, 1997 produced, as described above, a 13-km high ash column that produced perceptible ashfalls in high population-density areas, including Mexico City. At that time, the phases of the VTLAS were not clearly defined, and it was put in red for a few hours. However, different perceptions from federal and state authorities prevented an evacuation that finally proved unnecessary. An analysis of that situation ended in the definition of the phases within the colors as described in Table 4.

The management of the December 2000 eruption, which had very clear precursors, differed greatly from that for the June 1997 event. The colors and phases of the VTLAS were defined according to a radius prescribed by the SC. When the increased volcanic activity put the Traffic light in Yellow-3, that radius was extended to 12 km, which narrowly excluded the closest towns to the volcano. When the 24-hour forecast was communicated to the National Security Committee, the radius was increased to 13 km, and a red condition was set, prompting the preventive evacuation of the towns within that radius.

One of the main difficulties in the management of that crisis was the overreaction of the local authorities in small towns outside, but near the security radius. When they learned that some towns were being evacuated, they decided to order evacuation of their towns without waiting for confirmation of the National Security Committee. The number of people evacuated, estimated in about 41,000 thus exceeded expectations. The criterion for the return of these people to their homes was thus not well defined, and some of them remained up to 10 days in the temporary shelters. This kind of situation has proved very difficult to correct, since it requires adding some sort of “negative” alert to the safe areas close to the critical areas. This problem has not yet been solved.

## 7. Conclusions

Volcanic risk has two components: probability of occurrence of a given hazardous manifestation, and probability of loss of exposed population and property. The latter may be reduced through a proper preparedness. The effectiveness of the preparation measures depends, among other factors, on the degree of awareness and perception of the destructive power of different volcanic phenomena. This awareness may be low among people and authorities in a volcano with a low eruption rate. Such was the case of Popocatépetl Volcano, where a large population had lived for centuries perceiving it as a “smoking mountain” capable only of the type of minor activity reflected in its name. Knowledge of large eruptions in the distant past has been lost, except for a small academic community.

When the volcano reawakens and the possibility of a major eruption remains uncertain, the problem of dissemination of the changing risk concepts among a large population measured in millions becomes increasingly difficult as rumors and diverging opinions spread. After the destructive 1985 Mexico earthquake and particularly from the beginning of the Popocatépetl activity in 1994, a recognition of the political value of disaster prevention translated into a shift from a mostly hazard-led approach into a vulnerability-reduction driven approach.

The first step in the move into a disaster prevention policy was finding a communication tool that was proactive, efficient, unambiguous and culturally adequate. This tool had to be capable of distributing critical information among a large population in a short time, and contain enough clear information to mitigate as much as possible any potential loss, through the reduction of uncoordinated response and panic. Such a communication tool is the VTLAS, a simplified protocol in which the state of activity of the volcano is translated into a listing of the most probable scenarios by the scientific committee, allowing scientists to include greater latitude of opinions. Then, the likely scenarios are translated into a state of alert of the responsible authorities and the threatened population. This system won great acceptance among the public and the media. It still presents, however some difficulties in that local authorities have a tendency to overreact.

## Acknowledgments

We are grateful to the National System of Civil Protection of Mexico (SINAPROC) and the National Center of Disaster Prevention (CENAPRED) for providing valuable information on the management of the Popocatépetl Volcano crisis. We thank the reviewers for their comments that greatly helped to improve this paper. This research was partially funded by DGAPA (UNAM) grant IN-110502, and in its early stage also by CONACYT 25497-T grant, for which we are grateful.

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