Estimation of Volcanic Hazards from Tephra Fallout

By Charles B. Connor,[1] Brittain E. Hill,[2] Brandi Winfrey,[3] Nathan M. Franklin,[4] and Peter C. La Femina[5]

Abstract: The goal of probabilistic volcanic hazard assessment is to translate complex volcanological data and numerical models into practical hazard estimates for communities potentially affected by volcanic eruptions. Probabilistic volcanic hazard assessment quantifies volcanic hazards and illustrates uncertainties about the magnitude and consequences of volcanic activity. Planning based on probabilistic volcanic hazard assessment has the potential of mitigating the effects of volcanic eruptions when they occur. This paper presents an approach developed to estimate volcanic hazards related to tephra fallout and illustrates this approach with a tephra fallout hazard assessment for the city of León, Nicaragua, and the surrounding area. Tephra fallout from eruptions of Cerro Negro volcano has caused damage to property and adverse health effects and has disrupted life in this area. By summarizing the geologic and historical records of past eruptions of Cerro Negro on a probability tree, it is shown that the inhabitants of León can expect >1 cm of tephra accumulation from approximately 30% of eruptions, and >4 cm of tephra accumulation from approximately 9% of eruptions of Cerro Negro volcano. This historical record is augmented with simulations of tephra dispersion that estimate the likelihood of tephra accumulation given a range of eruption magnitudes and that map the expected distribution of tephra over a broader region. An upper limit value of 0.5 m is calculated using the tephra dispersion model. Without a fundamental change in the eruptive behavior of Cerro Negro, tephra accumulation in León is not expected to exceed this value.

INTRODUCTION

Planners and the communities they serve need to know what to expect from volcanic eruptions. Volcanologists can provide the information required to develop strategies for volcanic hazard mitigation and to weigh the relative costs of mitigation efforts. Information about volcanic hazards is best presented in the form of probabilistic hazard assessments, combining elements of the geologic record, numerical simulation of volcanic eruptions, and an accurate picture of the natural uncertainty in estimates of eruption magnitude and timing. Here, steps are outlined for a probabilistic hazard assessment of one aspect of volcanic eruptions: tephra fallout. Other phenomena that impact communities near volcanoes, such as pyroclastic flows and lahars, may be treated in a similar fashion, but require separate hazard analyses.

Tephra fallout results from explosive volcanic activity. Tephra, colloquially referred to as volcanic ash, consists of pyroclasts produced during volcanic eruptions and accidental lithic fragments incorporated in the eruption. Tephra fallout results when tephra is carried aloft in a volcanic eruption column and subsequently is deposited by sedimentation out of the volcanic plume, sometimes at great distances from the volcano (Fig. 1) (Fisher and Schmincke 1984; Sparks et al. 1997).

Magnitudes of volcanic eruptions are classified using the volcano explosivity index (VEI) (Newhall and Self 1982; Simkin and Siebert 1994), which primarily reflects eruption volume and the height of the eruption column. Large eruptions (VEI 4–6), such as the May 18, 1980, eruption of Mount St. Helens, and the June 15, 1991, eruption of Mount Pinatubo, produce significant tephra accumulation at great distances from erupting volcanoes, resultin in major disruptions for society [e.g., Sarna-Wojcicki et al. (1981), Koyaguchi (1996), and Punongbayan et al. (1996)]. Even moderately sized volcanic eruptions (VEI 3) can significantly affect areas >10 km from the volcano due to tephra fallout [e.g., Hill et al. (1998)]. Tephra fallout can cause building collapse, disruption of power and water supplies, damage to mechanical systems such as vehicle engines, and widespread damage to agricultural products, including livestock. Although the consequences of tephra fallout may be less severe than other eruption phenomena, vulnerability is often much greater due to the wide dispersal of tephra in volcanic plumes. In some cases, the continual remobilization of tephra deposits by wind or surface-disturbing activities has resulted in respiratory ailments and related deleterious health effects (Baxter 2000). In recent years, attention has also focused on the harm to aircraft caused by tephra and the risks associated with such damage for airline passengers and cargo (Miller and Casadevall 2000).

The purpose here is to describe probabilistic methods for assessment of tephra fallout hazards. This study fo-

[1]Ctr. for Nuclear Waste Regulatory Analyses, Southwest Res. Inst., 6220 Culebra Rd., San Antonio, TX 78235-5166. E-mail: cconnor@swri.edu

[2]Ctr. for Nuclear Waste Regulatory Analyses, Southwest Res. Inst., 6220 Culebra Rd., San Antonio, TX.

[3]Ctr. for Nuclear Waste Regulatory Analyses, Southwest Res. Inst., 6220 Culebra Rd., San Antonio, TX.

[4]Ctr. for Nuclear Waste Regulatory Analyses, Southwest Res. Inst., 6220 Culebra Rd., San Antonio, TX.

[5]Ctr. for Nuclear Waste Regulatory Analyses, Southwest Res. Inst., 6220 Culebra Rd., San Antonio, TX.

Note. Discussion open until July 1, 2001. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 31, 2000. This paper is part of the ***Natural Hazards Review***, Vol. 2, No. 1, February, 2001. ©ASCE, ISSN 1527-6988/01/0001-0033–0042/$8.00 + $.50 per page. Paper No. 22160.

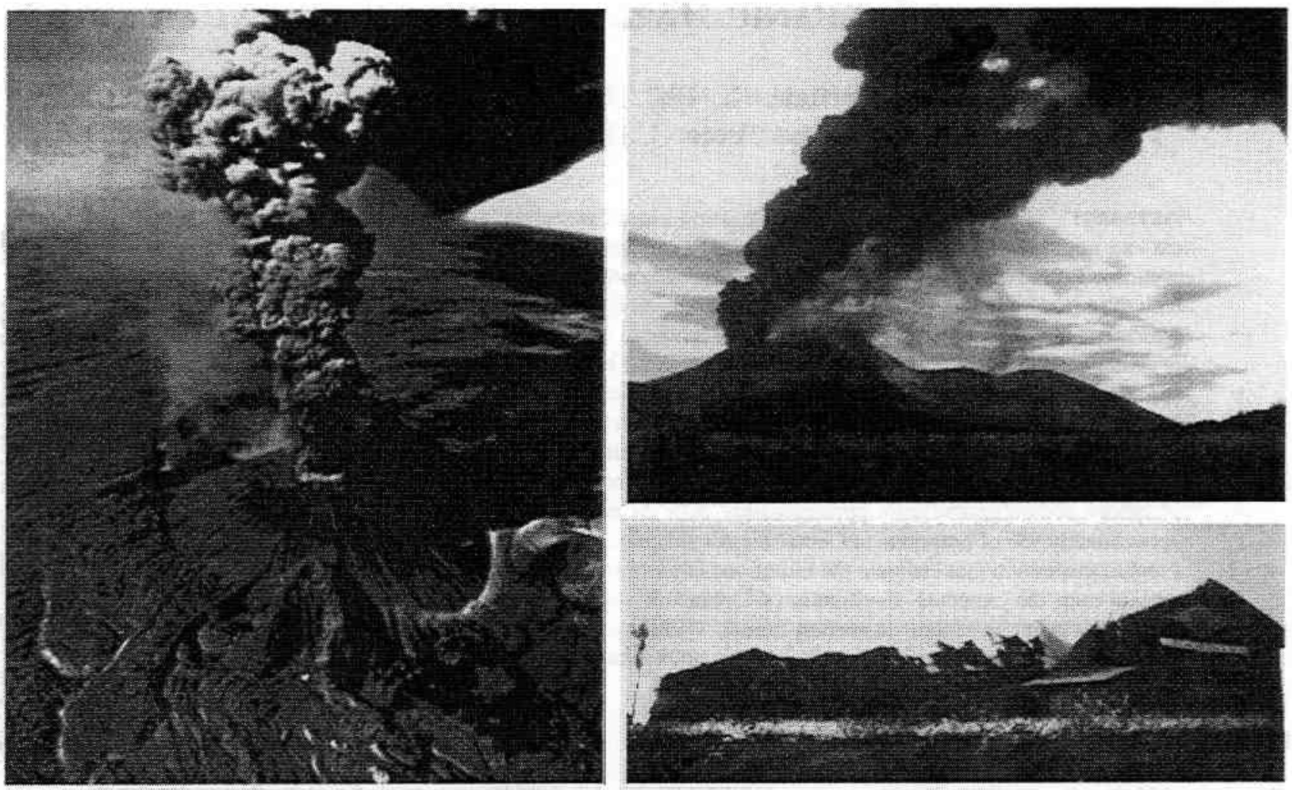

FIG. 1. Eruptions of Cerro Negro Volcano, Nicaragua: (Left) 1968 Eruption, from USGS Files; (Top Right) 1995 Eruption; (Bottom Right) Damage in León Resulting from 1992 Eruption

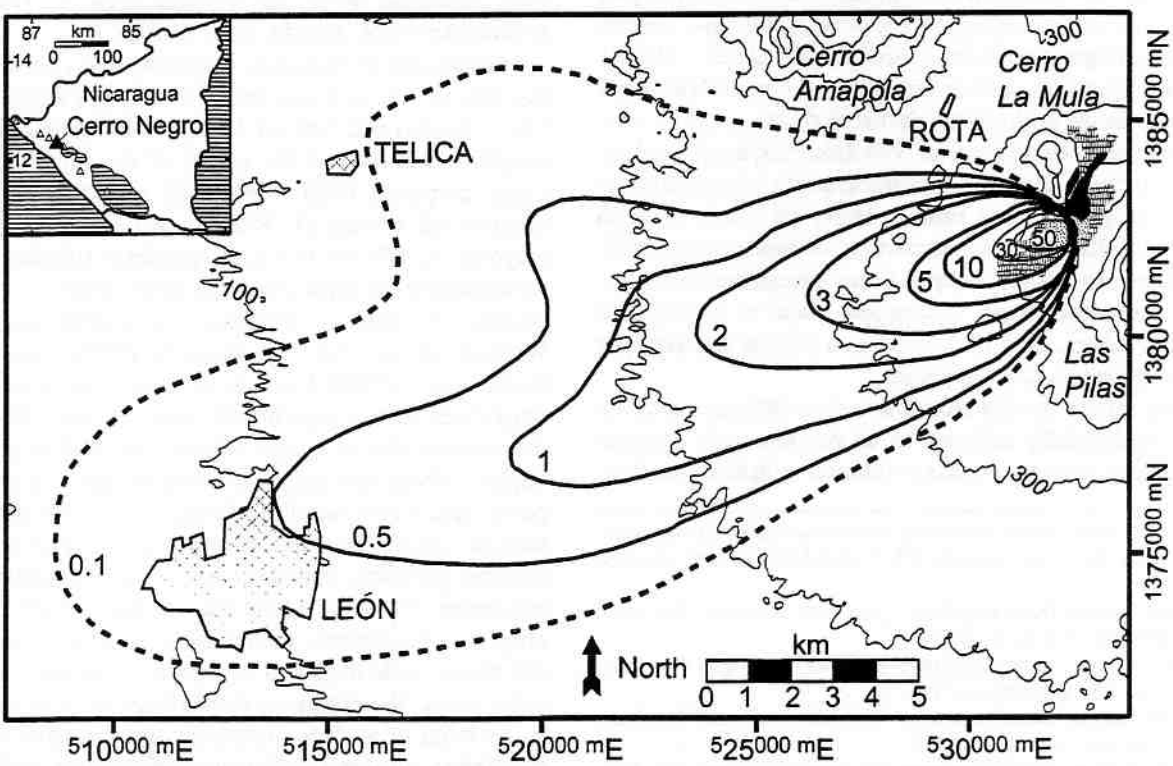

FIG. 2. Isopach Map for 1995 Eruption of Cerro Negro; Tephra Thickness Shown in cm [from Hill et al. (1998)]

cuses on tephra accumulation within tens of kilometers of the volcano, where tephra accumulation is most likely to cause damage. These methods are based on developing a conditional probability of tephra fallout, conditioned on the occurrence of eruptions. Thus, hazard assessments can be prepared in advance of episodes of volcano unrest, and mitigation strategies can be developed before volcanic crises occur. In this sense, long-term planning for tephra fall-

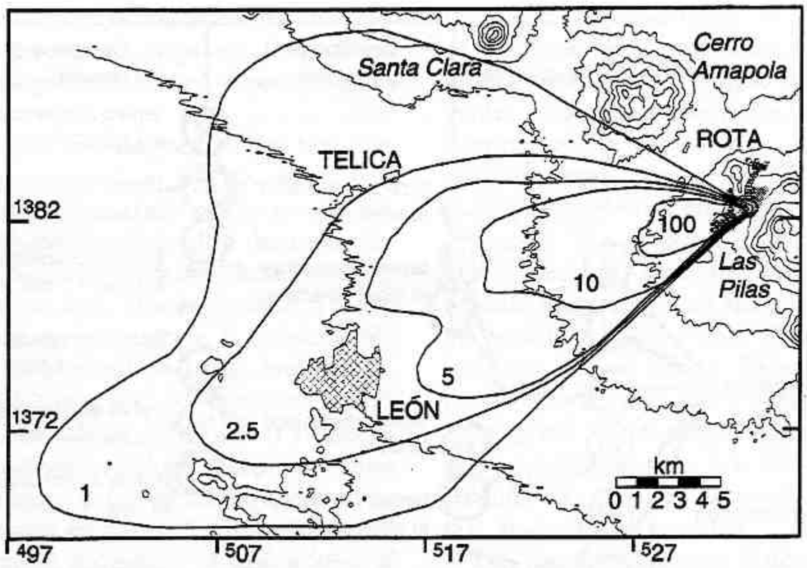

FIG. 3. Isopach Map for 1992 Eruption of Cerro Negro; Tephra Thickness Shown in cm [from Connor et al. (1993)]

out is a practical goal. To achieve this goal, is is necessary to combine geologic observations of past patterns of tephra accumulation with results of numerical simulations of tephra fallout. These results should account for the natural variability in the physical processes resulting in tephra fallout and the uncertainty related to the models here and observations of these phenomena. Steps in tephra fallout hazard estimation are described in the following, with special reference to Cerro Negro volcano, Nicaragua, a small-volume basaltic cinder cone that experiences comparatively frequent eruptions accompanied by tephra fallout (Figs. 2 and 3) and where we have implemented these steps previously (Hill et al. 1998).

TREATING TEPHRA FALLOUT AS CONDITIONAL PROBABILITY

Conditional probabilities enable volcanologists to consider a complicated series of events that typically comprise a volcanic eruption discretely. In the case of tephra fallout, it is simpler to estimate expected tephra accumulation, given eruption conditions, than to combine this disparate information into a single hazard forecast. For example, the geological record of numerical simulations can be used to infer P[tephra accumulation >1 cm at $(x, y)|$VEI2], the probability that tephra accumulation will exceed 1 cm at a given location (x, y) given that a volcanic eruption of intensity VEI 2 has taken place. The probability of an eruption occurring at all, or the probability that an eruption will follow a period of unrest, are treated as separate issues. Once the occurrence probability is determined, the unconditional probability of tephra fallout can be easily estimated.

Application of conditional probabilities is important for two reasons. First, volcanoes often experience prolonged periods of unrest, during which time the probability of an eruption changes considerably. Hazard assessment of tephra fallout for a given eruption made before the volcano unrest began should not require significant modifications during episodes of unrest, when attention is focused on monitoring. Second, the geologic record often provides information about the magnitude of eruptions, for instance, the thickness of tephra accumulated during past eruptions at a particular location, but comparatively little information about the timing and frequency of eruptions.

Conditional probabilities are easily visualized using event trees, which illustrate the observer's ability to predict outcomes (Schafer 1996). Often in volcanology, the ability to assign conditional probabilities to all possible outcomes is limited by lack of experience or lack of relevant information. In these circumstances, the trees may be only partially probabilized. An event tree for tephra fallout from Cerro Negro volcano (Fig. 4) has been constructed to illustrate their application in volcanology.

Cerro Negro has erupted 23 times since the volcano first formed in 1850 (McKnight 1995; McKnight and Williams 1997; Hill et al. 1998). Many of the early eruptions of Cerro Negro are poorly documented, but there is a reasonably complete record of tephra fall volumes since 1900. Since 1968, four eruptions have occurred at Cerro Negro (Table 1) that produced tephra fall volumes $>1 \times 10^6$ m^3, and three smaller eruptions have occurred. The most recent of these small eruptions was in August 1999 (Hill et al. 1999; La Femina et al. 1999). Based on a steady-state model of cumulative volume of material erupted from Cerro Nero, a volcanic eruption is expected before 2005 with 95% confidence (Hill et al. 1998, 1999). Many, but not all, of the eruptions of Cerro Negro have resulted in tephra deposition in the city of León, the second largest city in Nicaragua (population >200,000), located 20 km from Cerro Negro. In addition, an estimated 100,000 people live in the area surrounding León, with active agricultural communities located as close as 1 km from Cerro Negro. Tephra deposition in León has varied from trace amounts to 4 cm in 1992 (Fig. 3) (Connor

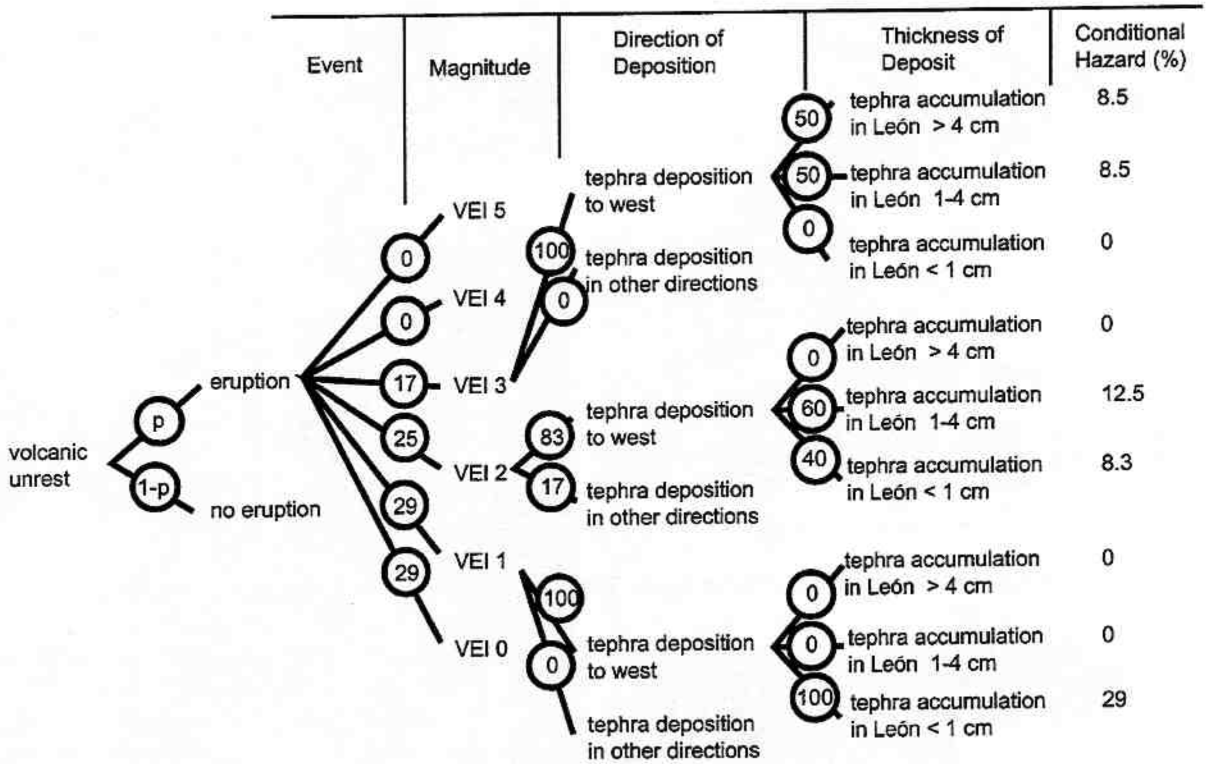

FIG. 4. Event Tree for Tephra Accumulation in León; Probabilities (in %) Based on Historical and Geologic Records of Past Cerro Negro Eruptions

TABLE 1. Cerro Negro Eruption Data

Year (A.D.) (1)	Duration (days) (2)	Fall volume (m^3) (3)	Fall volume DRE (km^3) (4)	Lava volume DRE (km^3) (5)	Column height (km) (6)	VEI (7)
1850	10	4.3×10^5	0.0002	0.0054	—	1
1867	16	7.4×10^6	0.0034	NA	3	2
1899	7	—	tr F	NA	—	1
1914	6	2.8×10^6	0.0013	NA	—	2
1919	10	—	tr F	NA	—	0
1923	49	1.7×10^7	0.0077	0.0100	2	2–3
1929	19	—	tr F	0.0001	—	0
1947	13	2.3×10^7	0.0110	0.0038	6	3
1948	1+	—	tr F	NA	—	0
1949	1+	—	tr F	NA	—	0
1950	26	2.8×10^6	0.0013	0.0001	1.5	2
1954	1+	—	tr F	NA	—	0
1957	20	2.8×10^6	0.0013	0.0045	2	2
1960	89	1.1×10^6	0.0005	0.0052	1	1
1961	1+	—	tr F	NA	—	0
1962	2	—	tr F	NA	—	1
1963	1+	—	tr F	NA	—	0
1968	48	9.7×10^6	0.0045	0.0069	2	2
1969	10	—	tr F	NA	—	0
1971	10.6	3.0×10^7	0.0139	tr L	4–6	3
1992	3.6	2.3×10^7	0.0110	NA	3–7	3
1995	79.0	—	tr F	tr L	—	1
1995	13.0	2.8×10^6	0.0013	0.0037	2–2.5	2
1999	3	8.4×10^5	0.0004	0.0006	1	1
Total	436	—	0.0578	0.0403	—	—

Note: DRE = dense rock equivalent; NA = no lava flows reported or very small volume; tr F = little appreciable tephra fallout occurred or was likely; tr L = very little volume lava flows reported.

et al. 1993). In the 1992 eruption, at least 2 people were killed and 146 were injured through building collapse, over 12,000 people were evacuated, and $19,000,000 of crops and infrastructure were destroyed (Organización 2000). Rates of respiratory and intestinal diseases increased by factors of 4 to 6 in the month following the 1992 eruption (Malilay et al. 1997). The significantly smaller 1995 (Fig. 2) eruption still displaced 1,200 people and destroyed $700,000 of crops and infrastructure (Organización 2000). Future tephra eruptions from Cerro Negro clearly present a significant hazard to people in this area.

Conditional probabilities are assigned to the branches of the event tree (Fig. 4) based on this record of past volcanic activity (Table 1). The event tree is incomplete because there is no probability assigned to the transition from volcanic unrest to volcanic eruption. There is simply inadequate data available to make this assessment at Cerro Negro. Given a volcanic eruption, there is a reasonably equal probability of VEI 0–2 and a slightly lower probability of VEI 3 and VEI 2 eruptions. No eruptions of VEI >3 have occurred at Cerro Negro. The VEI 0 eruptions do not produce significant tephra fallout, except very close to the volcano, and are not considered further on the tree. Nearly all of the explosive eruptions that have occurred (VEI 1–3) have resulted in deposition of tephra west of the volcano, toward the city of León. The tree is branched further into tephra accumulation <1, 1–4, and >4 cm. This bifurcation reflects both the way past tephra accumulation has been reported in León (McKnight 1995; Hill et al. 1998) and the severity of the consequences of the tephra accumulation.

Based on the geologic and historical records of volcanic eruptions at Cerro Negro, P[tephra accumulation >4 cm|volcanic eruption] = 8.5% and P[tephra accumulation >1 cm|volcanic eruption] = 29.5% (Fig. 4). So, although the record is limited (a ubiquitous circumstance in volcanology), the event tree provides a concise summary of the nature of past volcanic activity and its consequences for the city of León.

MODELING TEPHRA FALLOUT NUMERICALLY

The goal of modeling tephra fallout using numerical simulations is to provide a path from the geological and historical records of tephra accumulation to estimation of parameter distributions and ultimately to probabilistic estimates of tephra fallout hazard. Why are these additional steps necessary? Numerical simulation of geologic phenomena is a complex undertaking and modeling tephra fallout is certainly no exception. It would be ideal if the geologic and historical records provided an adequate picture of the frequency distribution of tephra fallout, and if, as a consequence, one could have a great deal of confidence in hazard estimates solely based on this record. Unfortunately, this is not the case. The geologic and historical records are insufficient as the sole basis for hazard assessment for several important reasons.

First, the geologic record is invariably sparse. In applying probabilistic techniques, it is assumed that there are parameters, such as mean and standard deviation, that describe the frequency distribution of tephra accumulation in a given area. Given a large number of events, one would expect the values of these parameters to converge toward a fixed limit. But with few events (e.g., <20 well-documented eruptions of Cerro Negro), there is no reason to believe with confidence that the frequency distribution of outcomes (e.g., thickness of tephra in León) is well represented by the geologic record, or that the limiting values of the parameters that characterize the frequency distribution are known [e.g., von Mises (1957)]. Probabilistic hazard assessments based on poorly known frequency distributions are highly uncertain.

Second, the geologic record is biased toward large events because these are more likely to be preserved. Smaller, generally more frequent, eruptions may leave no discernible geologic record. Conversely, the historical record may also be biased. Because of its brevity, the historical record often poorly reflects the full range of activity a given volcano has experienced. At Cerro Negro, given its short history, it is unlikely that the full range of potential eruptions is captured in the range of eruptions that have already occurred.

The disparity between historical and geologic records is particularly evident at Colima volcano, Mexico, where there is nearly complete disjunction between the historical and the stratigraphic records. Dozens of explosive eruptions have been recorded in the last 400 years, but only a single scoria layer has been preserved in the geological record for that period (Navarro and Luhr 2000). It is clear that at Colima volcano the preserved sequence includes just a fraction of the eruptive events, biasing the geologic record toward large eruptions. Nevertheless, the style of eruptive activity may have also changed over time. Modeling these data and estimating parameter distributions that best fit the data help resolve this parity. For example, if complex, multimodal parameter distributions are needed to model the historical and geologic data sets together, nonstationary behavior in eruption style may be indicated. Alternatively, if comparatively simple parameter distributions model both historical and geologic data sets, then the brevity of the historical record may account for the disparity. This disjunction between geologic and historical data sets is a classic situation, and numerical modeling provides insight into its origin and implications for probabilistic volcanic hazard assessment.

Third, hazard estimates based on the geologic record are difficult to update, as more information about changing conditions becomes available. Although not the focus of this paper, if the goal is to update probabilistic volcanic hazard forecasts in near real time, a model of tephra fallout is required (Carey 1996).

General Model Description

The overall benefit of numerical simulation lies in the promise of improved ability to quantify the expected variability in the volcanic system and consequently to improve hazard estimates. Development of tephra fallout models have been recently reviewed by Carey (1996), Sparks et al. (1997), and Rosi (1998). The present study illustrates the integration of tephra fallout models into a probabilistic volcanic hazard assessment using the model developed by Suzuki (1983) and subsequently modified and applied to volcanic eruptions by Armienti et al. (1988), Glaze and Self (1991), Jarzemba (1997), and Hill et al. (1998). Suzuki's model is empirical; the erupting column is treated as a line-source reaching a maximum height governed by the energy and mass flow of the eruption. A linear decrease in the upward velocity of particles is assumed, resulting in segregation of tephra particles in the ascending column by settling velocity, which is a function of grain size, shape, and density. Tephra particles are removed from the column based on their settling velocity, the decreasing upward velocity of the column as a function of height, and a probability density function that attempts to capture some of the natural variation in the parameters governing particle diffusion out of the column. Dispersion of the tephra that diffuses out of the column is modeled assuming a uniform wind field and is governed by the diffusion-advection equation with vertical settling. Thus, this model relies on estimation of numerous parameters that describe the volcanic eruption and the atmosphere it penetrates. Although not as comprehensive in addressing the physics of the eruption column [cf. Woods (1988, 1995)], the computational ease of the approach of Suzuki (1983) makes it a worthwhile method for hazard assessment, especially in light of the practical difficulties inherent in characterizing the variability in eruption and meteorological parameters [e.g., GVN (1999)].

This model abstracts the thermo-fluid-dynamics of ash dispersion in the atmosphere using the following expression:

$$X(x, y) = \int_{\phi_{\min}}^{\phi_{\max}} \int_0^H \frac{5 f_Z(z) f_\Phi(\phi) Q}{8\pi C (t + t_s)^{5/2}} \cdot \exp\left[-\frac{5((x - ut)^2 + y^2)}{8C(t + t_s)^{5/2}}\right] dz\, d\phi \tag{1}$$

where X = mass of tephra accumulated at geographic location (x, y) relative to the position of the volcanic vent (x increases in the downwind direction, and y is orthogonal to this direction); $f_Z(z)$ = probability density function for diffusion of ash out of the eruption column, treated as a line-source extending vertically (z) from the vent to column height H; $f_\Phi(\phi)$ = probability density function for grain size ϕ; Q = total mass of material erupted; u = wind speed in the x-direction; t = tephra particle fall time; t_s = tephra diffusion time; and C = eddy diffusivity in the atmosphere.

In the implementation here, it is assumed that tephra particle diameter is distributed normally in phi units (ϕ) [e.g., a grain diameter of $1\phi = -\log_2$ (0.5 mm)]

$$f_\Phi(\phi) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{\phi - \mu^2}{2\sigma^2}\right] \tag{2}$$

where μ and σ = mean and standard deviation of particle diameter, respectively (Fisher and Schmincke 1984). The tephra particle fall-time in the atmosphere is given by (Suzuki 1983)

$$t = 0.752 \times 10^6 \left[1 - \exp\left(-\frac{0.0625z}{v_0(\phi)}\right)\right]^{0.926} \tag{3}$$

where z = height; and v_0 = settling velocity, which depends on particle diameter

$$v_0(\phi) = \frac{\rho_{\mathrm{ash}} g \phi^2}{9\eta p_f^{-0.32} + \sqrt{81\eta^2 p_f^{-0.64} + 1.5\rho_{\mathrm{ash}}\rho_{\mathrm{air}} g \phi^3 \sqrt{1.07 - p_f}}} \tag{4}$$

where ρ_{ash} = density of tephra particles, taken here to be independent of grain size; g = gravitational acceleration; η and ρ_{air} = air viscosity and density, respectively; and p_f = particle shape factor

$$p_f = \frac{p_b + p_c}{2p_a} \tag{5}$$

where subscripts a, b, and c refer to the diameter of the particle along its principle axes; and $p_a > p_b > p_c$. The complexity of the expression for unsettling velocity stems from the complex relationship between drag on the particle and the particle Reynolds number

$$\mathsf{R} = \frac{v(\phi)\phi}{v_{\mathrm{air}}} \tag{6}$$

where v_{air} = kinematic viscosity of air. At low R, the settling velocity of particles obeys Stokes' law. At higher R, however, there is a transition to inertial flow and finally turbulent boundary flow (Bonadonna et al. 1998). Eq. (4) is only one approximation to these conditions (Suzuki 1983; Armienti et al. 1988; Sparks et al. 1997; Bonadonna et al. 1998).

In addition to settling, tephra particles diffuse in the atmosphere as they advect downwind. The diffusion time in (1) is given by Suzuki (1983) as

$$t_s = \left[\frac{5z^2}{288C}\right]^{5/2} \tag{7}$$

derived from the assumption that the standard deviation of the tephra plume width is one-third the height [cf. Woods (1988)].

The probability density function $f_Z(z)$ describes the diffusion of tephra out of the erupting column and into the surrounding atmosphere where it is available for downwind transport

$$f_Z(z) = \frac{\beta w_0 Y(z) e^{-Y(z)}}{v_0(\phi) H (1 - (1 + Y_0) e^{-Y_0})} \tag{8}$$

$$Y(z) = \frac{\beta w(z)}{v_0(\phi)} \tag{9}$$

$$Y_0 = \frac{\beta w_0}{v_0(\phi)} \tag{10}$$

$$w(z) = w_0 \left[1 - \frac{z}{H}\right]^\lambda \tag{11}$$

where w_0 = initial eruption velocity at the vent. The parameter β controls the shape of function $f_Z(z)$. Larger values of β result in a greater proportion of tephra reaching high in the eruption column. The upward velocity of particles $w(z)$ is assumed to decrease with height as a function of the parameter λ, where for most applications $\lambda = 1$. Eqs. (9)–(11) differ slightly from those provided in Suzuki (1983) and are written to conserve mass in the eruption column.

In practice, eruption column height H, total eruption volume V, and eruption duration T are the best known parameters for a given eruption. Walker et al. (1984) applied

$$\frac{dV}{dt} = \left[\frac{H}{1.67}\right]^4 \qquad (12)$$

to estimate the mass eruption rate, where H is in kilometers and dV/dt is in cubic meters (dense rock equivalent). This application assumes that the eruption rate is constant over the duration of the eruption, i.e.

$$V = \frac{dV}{dt} T \qquad (13)$$

These relations provide a check on input parameters used in the Suzuki (1983) model.

Tephra Fallout Hazard Curves for Cerro Negro Volcano

In practice, the model is calculated numerous times using a range of input parameters (e.g., total mass, column height, etc.) that reflect the historical range of activity at Cerro Negro. Each realization represents a possible combination of eruption style, magnitude, duration, and atmospheric conditions that control the amount and distribution of tephra fallout. Using this stochastic approach, the range of likely eruption styles (VEI 0–3) and their consequences for tephra fallout hazard are evaluated.

Successful application of the model relies on well-chosen input parameters. It is the experience of the writers that model results are strongly controlled by eruption volume, column height, and eruption velocity. Eruption volumes were samples from a log-uniform random distribution with tephra volumes ranging from 5×10^5 to 1×10^8 m^3, based on estimates of the volumes of past eruptions. Column height was sampled from a uniform random distribution, U[2 km, 8 km]. The relationships between column height, mass flow, eruption duration, and total eruption volume [e.g., (12) and (13)] were used to check these input parameters. Eruptions with very long durations, >120 days, were eliminated from the sample set because long duration explosive activity at Cerro Negro has never occurred. Eruption velocity was sampled from a uniform random distribution U[50 m/s, 100 m/s], independent of mass flow. Wilson and Head (1981) suggested a relationship between eruption velocity and mass flow that, for Cerro Negro, yields eruption velocities much lower than the 75–100 m/s velocities that have been observed (Connor et al. 1993; Hill et al. 1998) or the eruption velocities predicted for buoyant tephra columns at low mass flow rates of 1×10^6 kg/s (Woods and Bursik 1991).

Wind speed and direction also have a strong influence on the tephra accumulation. At Cerro Negro, tradewinds are quite consistent. Average monthly wind direction is to the west or west southwest, and average wind speed on the ground is 4–6 m/s, with maximum wind speeds of 15 m/s measured during most months (National 2000). Fur-

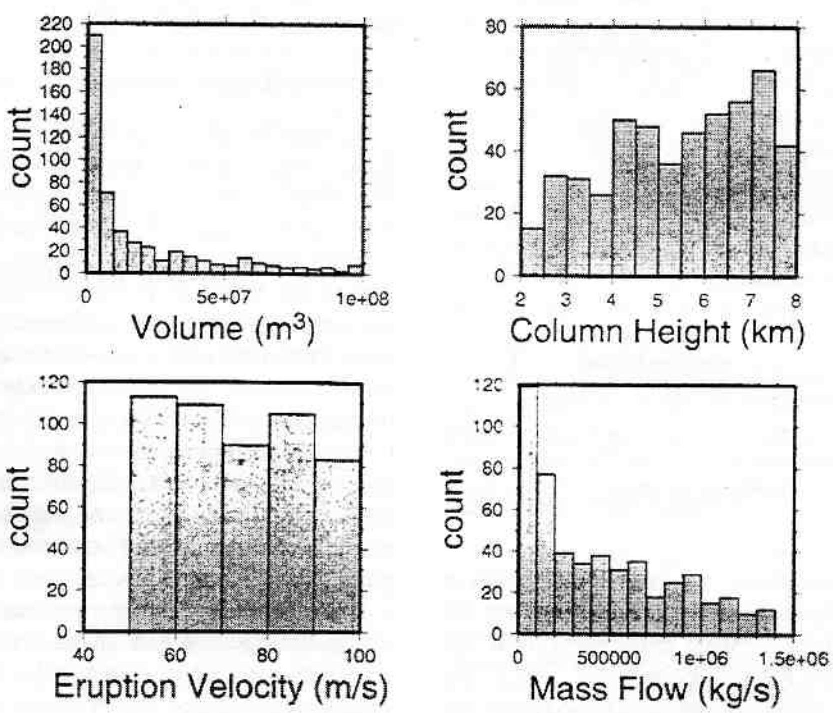

FIG. 5. Histograms for Several Input Parameters for Suzuki Model

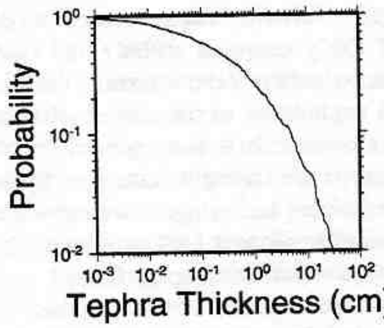

FIG. 6. Conditional Hazard Curve for Tephra Accumulation in León

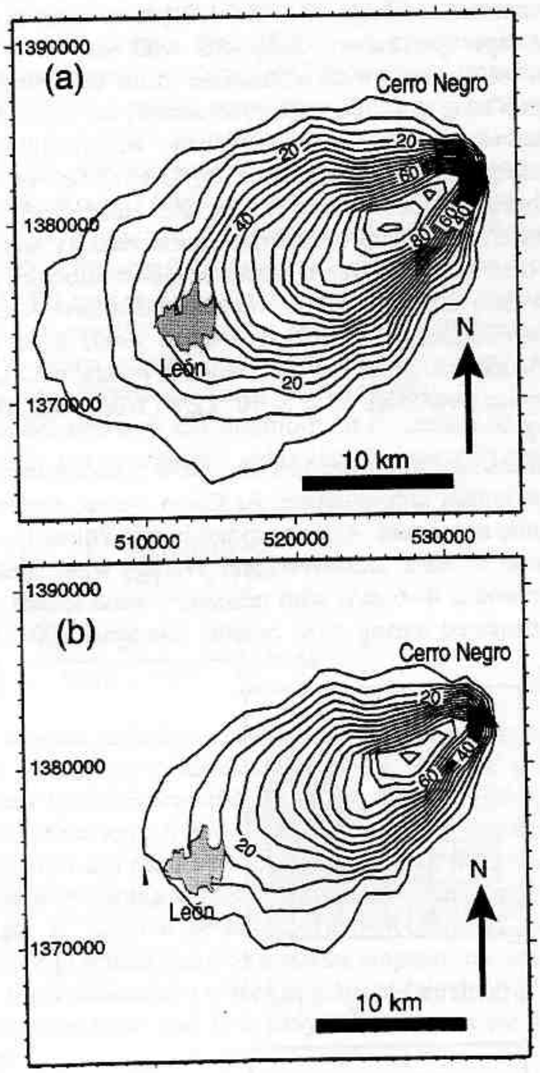

FIG. 7. Probability Maps for Tephra Accumulation from Eruption of Cerro Negro (Contoured in %, at 5% Contour Interval): (a) *P*[tephra > 1 cm|volcanic eruption]; (b) *P*[tephra > 4 cm|volcanic eruption]

thermore, with the exception of the 1914 eruption (McKnight 1995), all significant tephra deposition has occurred west of Cerro Negro, with León lying near the major axis of dispersion for the 1968, 1971, 1992, and 1995 eruptions (Figs. 2 and 3). Therefore, wind speed was sampled from a U[5 m/s, 15 m/s] distribution and wind direction from a $U[-5°, -35°]$ distribution, where wind direction is with respect to due west. In the absence of meteorological observations, it is assumed that these ranges apply to wind data at higher elevations. This assumption at least works well for the 1995 eruption, during which wind speeds in the tephra plume were 9 m/s (Hill et al. 1998).

Grain-size distribution was integrated from -5 to 5ϕ, with mean grain size = -1ϕ and standard deviation = 1ϕ. Clast density was varied as U[0.9 gm/cm^3, 1.2 gm/cm^3], equant grains were used ($p_f = 0.5$), and $\beta = 0.5$. This value for β forces a higher proportion of erupted pyroclasts to elevations close to the top of the eruption column, a choice consistent with field observations and thermo-fluid-dynamic models of volcanic plumes (Woods 1995).

Stochastically sampled distributions for volume, column height, and eruption velocity are shown in Fig. 5. Estimated mass flow given column height [(12)] is also shown. For these parameter distributions, simulated tephra accumulation in León varies from <<0.1 to 30 cm in the 500 realizations.

The results of the analysis are best illustrated using an exceedance probability plot, also known as a hazard curve. For this range of input parameters, 50% of eruptions result in tephra accumulation <0.2 cm in León (Fig. 6). Approximately 26% of eruptions result in tephra accumulation >1 cm, and 11% of eruptions result in tephra accumulation >4 cm, in reasonable agreement with the historical record. The numerical simulation suggests that P[tephra >10 cm in León|volcanic eruption] = 5%. Probability of tephra accumulation >1 and >4 cm is contoured for the region about Cerro Negro volcano in Figs. 7(a and b). These maps illustrate the expected outcomes of eruptions at Cerro Negro for the population living closer to the volcano than León.

Extreme Events at Cerro Negro

In addition to the probable outcomes summarized in Figs. 6 and 7, it is useful to produce worst-case scenarios of volcanic activity in order to communicate the potential magnitude of hazards. Worst-case scenarios bound the consequences of volcanic activity, with the goal of conveying the limits of potential volcanic devastation based on reasonable or conservative assumptions. Volcanologists often hesitate to convey worst-case scenarios because of the fear, often well-founded, and worst-case scenarios will be misinterpreted as "base case" or "expected" scenarios. Conversely, worst-case scenarios can be ridiculed as overly conservative or alarmist. Nevertheless, it is worthwhile for volcanologists and public officials to think freely about large magnitude events and their impact on risks to public health and safety.

Development of worst-case scenarios can be made palatable through the introduction of the concept of upper limit values (ULVs). Essentially, ULVs are deterministic assessments of hazard using conservative assumptions. The concept of ULVs (also known as screening distance values) was developed in seismic risk assessment for sensitive facilities, such as nuclear power plants, that must be located in areas of very low geologic risk. These techniques have now been extended to volcanic hazards for nuclear facilities (International 1997) and are readily adapted to general hazard mitigation efforts.

Accurate development of ULVs relies on basic geologic investigations at many volcanoes, not necessarily those most likely to erupt. For example, the recent (<5,000 year bp) history of Crater Lake suggests that eruptions in this magmatic system are highly unlikely in the coming decades. Nevertheless, the history of Crater Lake and ancestral Mount Mazama provides a benchmark for the potential magnitudes of future silicic volcanic eruptions in the Cascade mountains (Bacon 1983): In constructing hazard assessments for other Cascade volcanic systems, such as South Sister, geologic insights from studies of the Mount Mazama eruption can be considered through the use of ULVs. Similarly, the Katmai eruption of 1912 and the Mount Pinatubo eruption of 1991 (Newhall and Punongbayan 1996) should not be considered expected events in the Cascades during the next several decades, but such eruptions are completely within the realm of possibility and can be considered in hazards assessments through the use of ULVs.

As an example, a ULV for tephra accumulation in León is constructed, based on a set of parameters outside the range of past activity, but nonetheless possible, given eruptions from basaltic cinder cones in general. This model assumes an 8-km high eruption columns, 100-m/s eruption velocity, and total volume of 1×10^8 m^3. For comparison, the 71-day eruption of Tolbachik volcano, Kamchatka, sustained 13–10-km high eruption columns and erupted 9×10^8 m^3 (0.42-km^3 dense rock equivalent) of tephra (Doubik and Hill 1999). It is also assumed that León lies on the major axis of dispersion and that the wind speed is 15 m/s during the eruption. Such an eruption, larger than past eruptions at Cerro Negro, is at the approximate upper bound of VEI 3 activity. Given these parameters and based on the Suzuki model, the ULV for tephra accumulation in León is 47 cm.

DISCUSSION AND CONCLUSIONS

The hazard models presented here are strictly empirical, rather than predictive. The historical and geologic record of events is used to temper and refine the numerical analysis and to temper the interpretation of the results. Although short, the record of eruptions at Cerro Negro is more complete than many volcanoes. For many volcanoes, analogous volcanic eruptions at other volcanoes may be needed to augment the record and to completely reflect the natural variation in expected eruptions.

The Suzuki model does not capture the physics of volcanic eruption completely. Rather, this model simplifies the physics in several ways. For example, the wind field is considered to be uniform with height above the volcanic vent, and particle motion in the column is treated probabilistically rather than with analytical determinism. Used in a stochastic fashion and calibrated by independent observations, the model works reasonably well despite such limitations. This dynamic exists in much of volcanic hazard assessment. Other examples of the effective use of simplified models in volcanology include Iverson et al. (1998) and Wadge et al. (1994). When integrated with geologic data, as attempted here (Figs. 2 and 3), such simplified models become efficient tools for volcanic hazards mitigation. This is different from attempting to forecast the outcome of a specific eruption, during which some variables, such as atmospheric conditions, are possibly well known. Although more dramatic to forecast the trajectory of an ash cloud as an eruption progresses, it is extremely useful to provide communities with a long-term forecast, prior to volcanic activity, so that informed decisions about building location, construction, and response can be formulated.

For Cerro Negro volcano, it is concluded here from analysis of the geologic data and numerical simulation that, given a volcanic eruption, the probable tephra accumulation in León of >1 cm is approximately 29%, >4 cm is approximately 9%, and >10 cm is approximately 5%. For smaller, more frequent eruptions the analysis here relies most heavily on observation. For larger, less frequent eruptions, this analysis relies more on the results of the numerical simulation. The ULV for tephra accumulation in León is approximately 0.5 m. In other words, given the current knowledge about this volcano, no circumstances are envisioned under which an eruption would result in more than approximately 0.5 m of tephra deposition in León.

The main issues that emerge from application of this style of hazard assessment involve estimation of parameter distributions. For tephra accumulation, a clearer understanding of the links between magma properties and the parameters column height, eruption velocity, and total eruption volume has the potential of improving the hazard assessment. In time, the uniform random distributions used for parameters like eruption velocity might be replaced by more realistic distributions, or calculated directly from magma rheologic properties, as more about the physical basis of these links emerge. The importance of such links can only be appraised by progressing from the basic data and models through the hazard assessment. In this sense, results of probabilistic assessments can provide guidance about the volcanological research most likely to result in volcanic hazard reduction.

ACKNOWLEDGMENTS

The writers thank Ron Martin and Laura Connor for their assistance in coding and document preparation. Field assistance at Cerro Negro volcano by Wilfried Strauch and Marta Navarro of the Instituto Nicaragüense de la Estudios Territoriales is gratefully acknowledged. Reviews by James Weldy, Budhi Sagar, and an anonymous reviewer improved the manuscript. This manuscript documents work performed at the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-

97-09. The activities reported were performed for the NRC Office of Nuclear Safety and Safeguard, Division of Waste Management. This report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

APPENDIX. REFERENCES

Armienti, P., Macedonio, G., and Pareschi, M. (1988). "A numerical model for simulation of tephra transport and deposition: Applications to May 18, 1980, Mount St. Helens eruption." *J. Geophys. Res.*, 93, 6463–6476.

Bacon, C. R. (1983). "Eruptive history of Mount Mazama and Crater Lake Caldera, Cascade Range, U.S.A." *J. Volcanology and Geothermal Res.*, 18, 57–115.

Baxter, P. J. (2000). "Impacts of eruptions on human health." *Encyclopedia of Volcanoes*, H. Sigurdsson, ed., Academic, San Diego, 1035–1056.

Bonadonna, C., Ernst, G. G. J., and Sparks, R. S. J. (1998). "Thickness variations and volume estimates of tephra fall deposits: The importance of particle Reynolds number." *J. Volcanology and Geothermal Res.*, 69, 217–239.

Carey, S. N. (1996). "Modeling of tephra fallout from explosive eruptions." *Monitoring and mitigation of volcanic hazards*, R. Scarpa and R. Tilling, eds., Springer, Berlin, 429–461.

Connor, C. B., Powell, L., Strauch, W., Navarro, M., Urbina, O., and Rose, W. I. (1993). The 1992 eruption of Cerro Negro, Nicaragua: An example of Plinian-style activity at a small basaltic cinder cone, *Eos, Trans. Am. Geophys. Union*, 74, 640.

Doubik, O., and Hill, B. E. (1999). "Magmatic and hydromagmatic conduit development during the 1975 Tolbachik eruption, Kamchatka, with implications for hazards assessment at Yucca Mountain, NV." *J. Volcanology and Geothermal Res.*, 91, 43–64.

Fisher, R. V., and Schmincke, H.-U. (1984). *Pyroclastic rocks*, Springer, Berlin.

Glaze, L., and Self, S. (1991). "Ashfall dispersal of the 16 September 1986, eruption of Lascar, Chile, calculated using a turbulent diffusion model." *Geophys. Res. Letters*, 18, 1237–1240.

GVN. (1999). "Report on the October eruption of Guagua Pinchincha volcano, Ecuador." *Global Volcanism Network Bull.*, 24, 10.

Hill, B. E., et al. (1999). "August 1999 eruption of Cerro Negro volcano, Nicaragua, successfully forecast using time-volume relationships." *Eos, Trans. Am. Geophys. Union*, 80(46), F1111.

Hill, B. E., Connor, C. B., Jarzemba, M. S., La Femina, P. C., Navarro, M., and Strauch, W. (1998). "1995 eruptions of Cerro Negro volcano, Nicaragua and risk assessment for future eruptions." *Geological Soc. of Am. Bull.*, 110, 1231–1241.

International Atomic Energy Agency. (1997). *Volcanoes and associated topics in relation to nuclear power plant siting, Provisional Safety Standard Ser. 1.*

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

Jarzemba, M. S. (1997). "Stochastic radionuclide distributions after a basaltic eruption for performance assessments for Yucca Mountain." *Nuclear Technol.*, 118, 132–141.

Koyaguchi, T. (1996). "Volume estimation of tephra-fall deposits from the June 15, 1991, eruption of Mount Pinatubo, by theoretical and geological methods." *Fire and mud, eruptions, and lahars, of Mount Pinatubo, Philippines*, C. G. Newhall and R. S. Punongbayan, eds., University of Washington Press, Seattle, 583–600.

La Femina, P. C., et al. (1999). "Shallow dike emplacement during August, 1999, seismic and volcanic activity at Cerro Negro, Nicaragua." *Eos, Trans. Am. Geophys. Union*, 80(46), F972.

McKnight, S. B. (1995). "Geology and petrology of Cerro Negro volcano, Nicaragua." Master's thesis, Arizona State University, Tempe, Ariz.

McKnight, S. B., and Williams, S. N. (1997). "Old cinder cone or young composite volcano? The nature of Cerro Negro, Nicaragua." *Geol.*, 25, 339–342.

Malillay, J., Real, M. G., Vanegas, A. R., Noji, E., and Sinks, T. (1997). "Vigilancia de la salud pública después de una erupción volcánica: Lecciones aprendidas en Cerro Negro, Nicaragua, 1992." *Revista Panamericana de Salud Pública*, 1(3), 213–219 (in Spanish).

Miller, T. P., and Casadevall, T. J. (2000). "Volcanic ash hazards to aviation." *Encyclopedia of volcanoes*, H. Sigurdsson, ed., Academic, San Diego, 915–930.

National Climatic Data Center. (2000). "International station meteorological climate summary, STA 787410, Managua—Telecom summary." ⟨http://www.ncdc.noaa.gov⟩.

Navarro Ochoa, C., and Luhr, J. F. (2000). "Late-Holocene tephrachronology at the Colima volcanic complex, Mexico." *Proc., Colima Volcano 7th Int. Meeting*, 44–45.

Newhall, C. G., and Punongbayan, R. S. (1996). "The narrow margin of successful volcanic-risk mitigation." *Monitoring and mitigation of volcanic hazards*, R. Scarpa and R. Tilling, eds., Springer, Berlin, 807–838.

Newhall, C. G., and Self, S. (1982). "The volcanic explosivity index (VEI): An estimate of explosion magnitude for historical volcanism." *J. Geophys. Res.*, 87, 1231–1238.

Organización Panamericana de la Salud. (2000). "Datos históricos de desastres naturales que han afectado Nicaragua en los años." ⟨http://www.ops.org.ni/desastre/d-civil/i-history.htm⟩ (in Spanish).

Punongbayan, R. S., et al. (1996). "Eruption hazard assessments and warnings." *Fire and mud, eruptions and lahars of Mount Pinatubo, Philippines*, C. G. Newhall and R. S. Punongbayan, eds., University of Washington Press, Seattle, 67–86.

Rosi, M. (1998). "Plinian eruption columns: Particle transport and fallout." *From magma to tephra, modelling physical processes of explosive volcanic eruptions*, A. Freundt and M. Rosi, eds., Elsevier Science, Amsterdam, 139–172.

Sarna-Wojcicki, A. M., Shipley, S., Waite, R. B., Dzuirisin, D., and Wood, S. H. (1981). "Areal distribution, thickness, mass, volume, and grain size of air-fall ash from the six major eruptions of 1980." *The 1980 eruptions of Mount St. Helens, Washington, Prof. Paper 1250*, P. W. Lipman and D. R. Mullineaux, eds., U.S. Geological Survey, 577–600.

Shafer, G. (1996). *The art of causal conjecture*, MIT Press, Cambridge, Mass.

Simkin, T., and Siebert, L. (1994). *Volcanoes of the world*, 2nd Ed., Smithsonian Institution Press, Washington, D.C.

Sparks, R. S. J., et al. (1997). *Volcanic plumes*, Wiley, West Sussex.

Suzuki, T. (1983). "A theoretical model for the dispersion of tephra." *Arc volcanism: Physics and tectonics*, D. Shimozuru and I. Yokoyama, eds., Terra Scientific Publishing, Tokyo, 95–103.

von Mises, R. (1957). *Probability, statistics, and truth*, 2nd Revised English Ed., Dover, New York.

Wadge, G., Young, P. A. V., and McKendrick, I. J. (1994). "Mapping lava flow hazards using computer simulation." *J. Geophys. Res.*, 99, 489–504.

Walker, G. P. L., Self, S., and Wilson, L. (1984). "Tarawera 1886, New Zealand—A basaltic plinian fissure eruption." *Volcanology and Geothermal Res.*, 21, 61–78.

Wilson, L., and Head, J. (1981). "The ascent and eruption of magma on the Earth and Moon." *J. Geophys. Res.*, 86, 2971–3001.

Woods, A. W. (1988). "The fluid dynamics and thermodynamics of eruption columns." *Bull. Volcanology*, 50, 169–193.

Woods, A. W. (1995). "The dynamics of explosive volcanic eruptions." *Rev. in Geophys.*, 33, 495–530.

Woods, A. W., and Bursik, M. I. (1991). "Particle fallout, thermal disequilibrium, and volcanic plumes." *Bull. Volcanology*, 53, 559–570.