Estimation of Volcanic Hazards from Tephra Fallout

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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-

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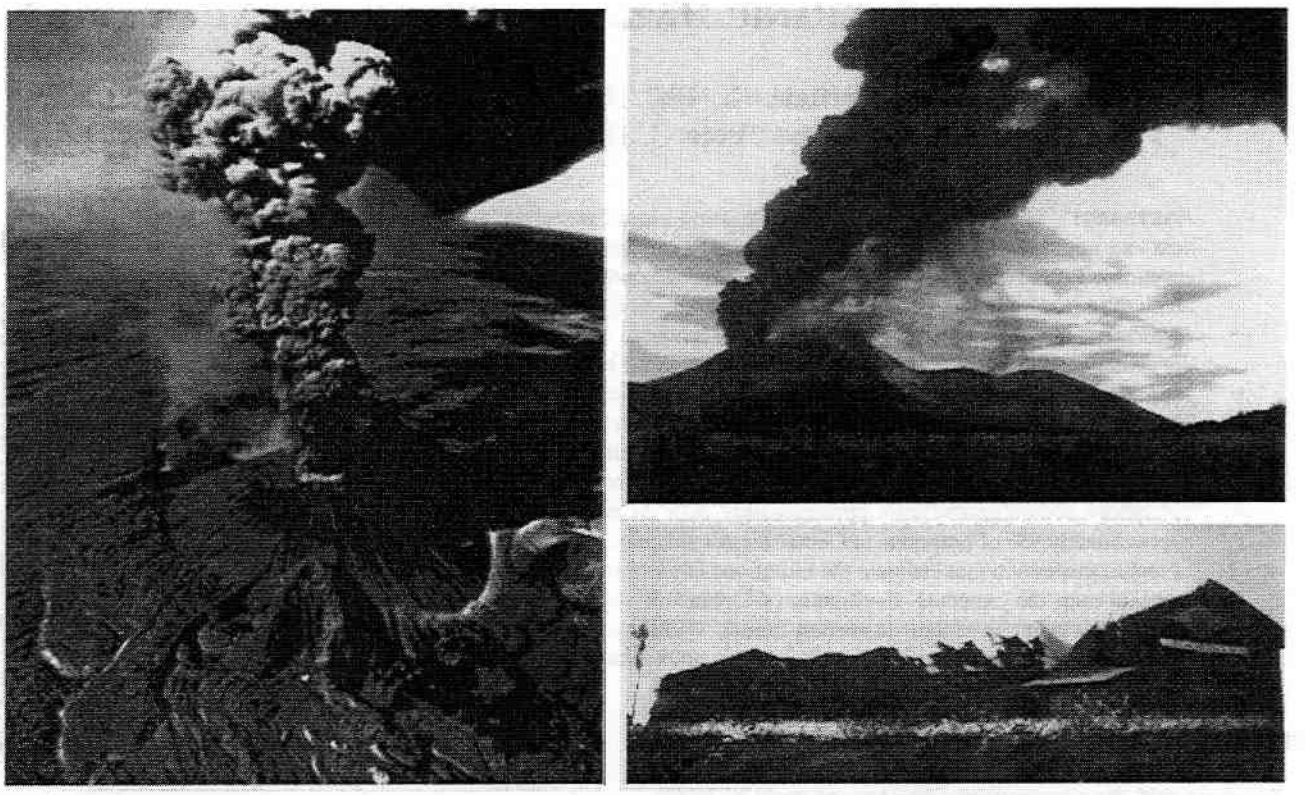

FIG. 1. Eruptions of Cerro Negro Volcano, Nicaragua: (Left) 1968 Eruption, from USGS Files; (Top Right) 1995 Eruption; (Bottom Right) Damage in León Resulting from 1992 Eruption

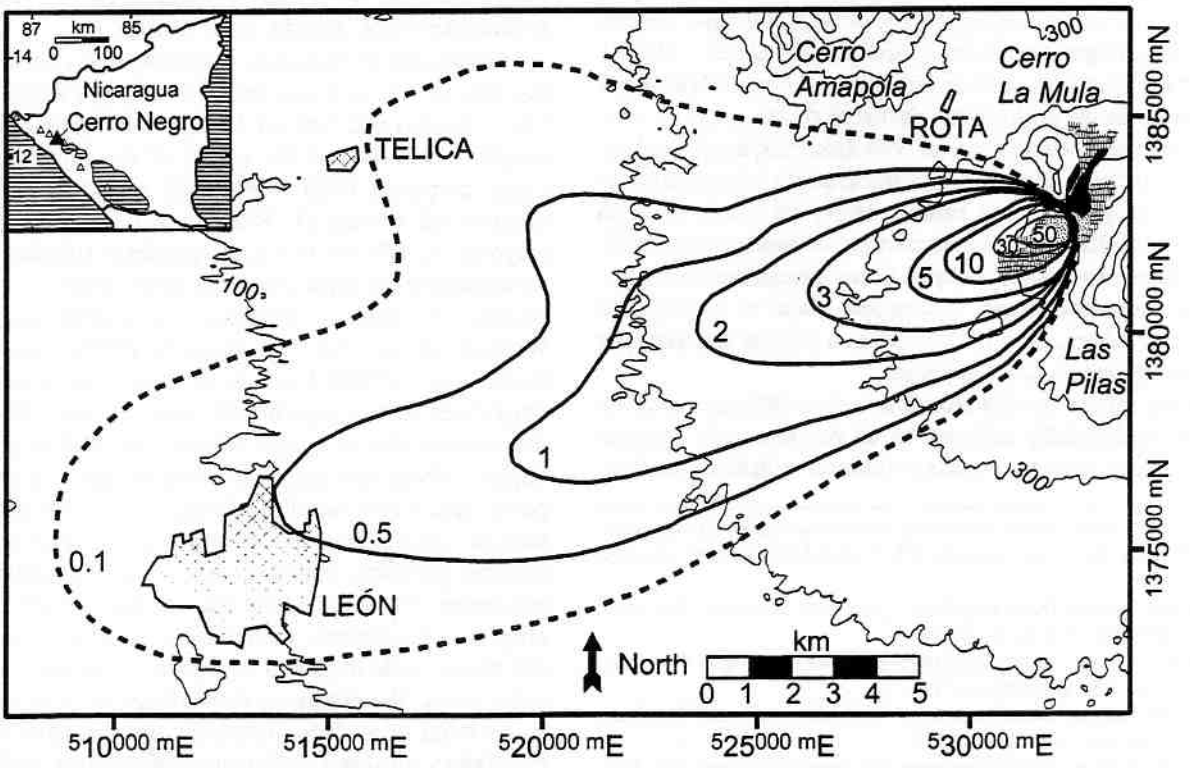

FIG. 2. Isopach Map for 1995 Eruption of Cerro Negro; Tephra Thickness Shown in cm [from Hill et al. (1998)]

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-

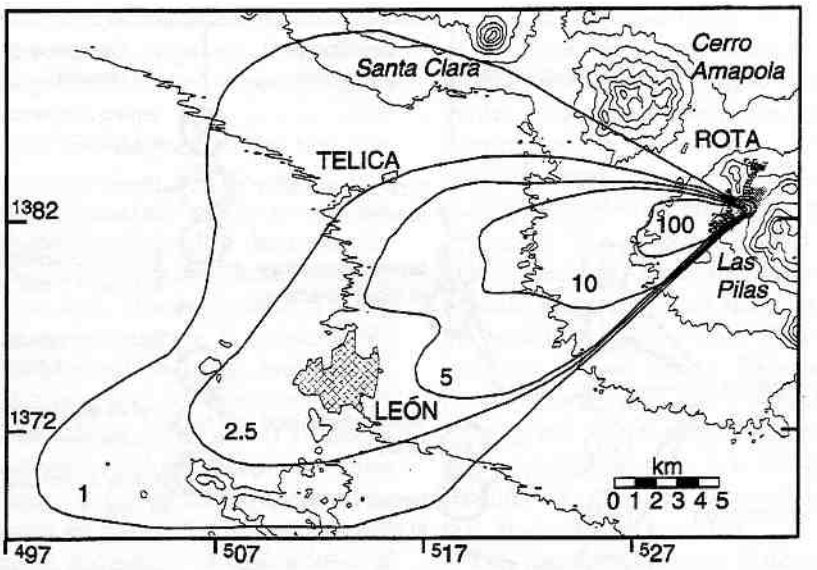

FIG. 3. Isopach Map for 1992 Eruption of Cerro Negro; Tephra Thickness Shown in cm [from Connor et al. (1993)]

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

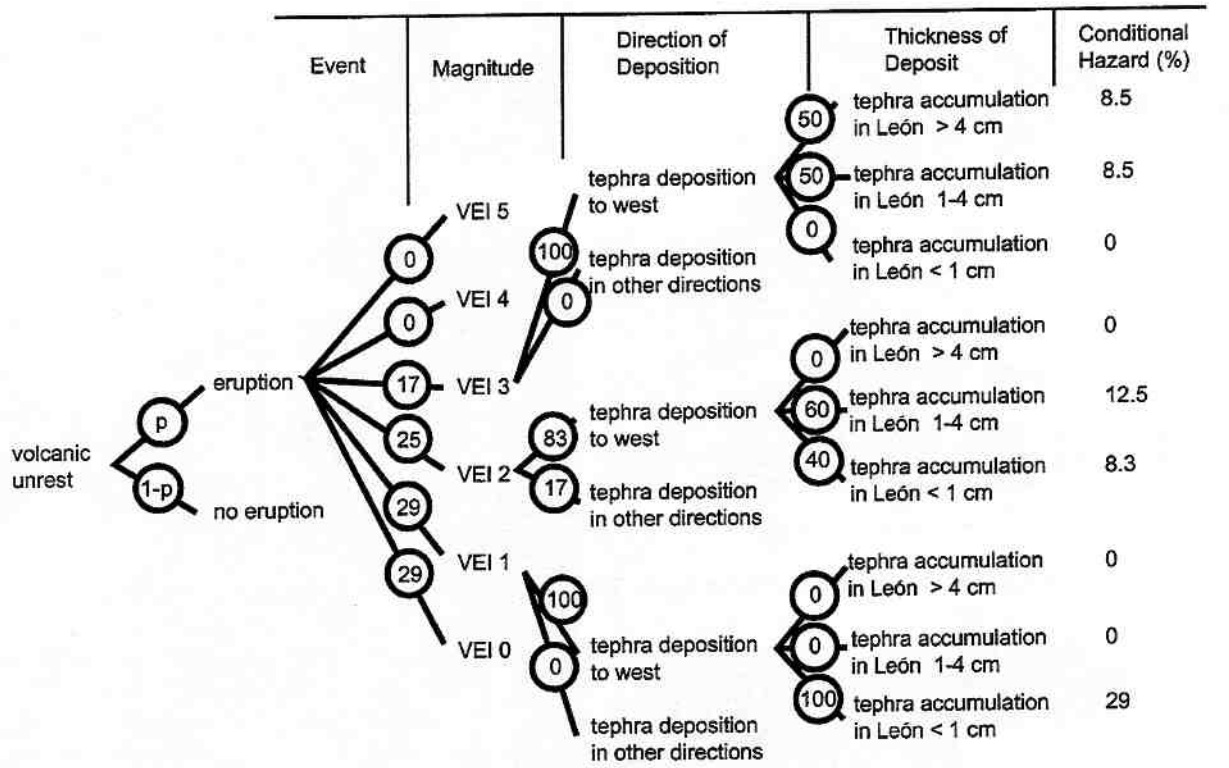

FIG. 4. Event Tree for Tephra Accumulation in León; Probabilities (in %) Based on Historical and Geologic Records of Past Cerro Negro Eruptions

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