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# *Volcanic hazards in Nicaragua: Past, present, and future*

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## ABSTRACT

**We review the most important types of volcanic hazards that have occurred in Nicaragua during the past ~40,000 yr and that are expected to occur in the future. Population density within the potential hazard area is clearly essential in defining and understanding volcanic hazard and risk. There are three main groups of volcanic events that pose major hazards: Group 1 comprises several types of explosive volcanic eruptions that impact society (people and infrastructure) directly. The most hazardous types are pyroclastic surges, particularly those generated by water-magma interaction, pyroclastic fallout, and pyroclastic flows, as well as tsunamis generated by volcanic eruptions within and close to Nicaragua's large lakes. Group 2 includes nonexplosive volcanic activity such as lava flows and the permanent or episodic emission of volcanic gases from open vents. Group 3 comprises chiefly lahars generated by mixing of volcanic debris with water and volcano flank collapses (landslides) sometimes unrelated to synchronous volcanic eruptions but being conditioned chiefly by the stability of a volcanic edifice. We discuss the present database on the age and type of the most recent eruptions emphasizing those that potentially pose major hazards to the populated areas. These include volcanogenic tsunamis in Lake Managua and**

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**Lake Nicaragua, scoria cone and maar formation chiefly in the western part of Managua, and major explosive eruptions of Chiltepe and Masaya volcanoes, a large eruption from Masaya volcano having devastated the entire area of present Managua only ~2000 yr ago. We discuss the most important techniques for monitoring volcanoes to detect unrest and predict the time and magnitude of upcoming eruptions, emphasizing techniques presently employed in Nicaragua. Finally, we address the subjects of risk assessment, including hazard and risk maps, and the importance of long-term development plans to reduce vulnerability.**

**Keywords:** debris flows, eruption forecasting, monitoring, tephrostratigraphy, tsunamis.

## INTRODUCTION

The subduction of the oceanic Cocos plate beneath Nicaragua (Fig. 1) is the common cause of the earthquakes, tsunamis, and volcanic eruptions that have repeatedly affected the country in the past (Carr et al., 1982; Carr, 1984; Protti et al., 1995; Ranero et al., 2000; Stoiber and Carr, 1973; Walker et al., 2001; Walther et al., 2000). The history of Nicaraguan arc volcanism has been studied by McBirney and Williams (1965), Weyl (1980), and Bice (1985). Carr et al. (1982) and Carr (1984) related the magmatic evolution of the arc to the structure and composition of the subducted slab. Weinberg (1992) studied the relationship between volcanism and subduction-related tectonics.

Every few years, one or more of the roughly 10 active volcanoes erupt along the volcanic front in Nicaragua. Major eruptions, or collapse of volcano flanks unrelated to synchronous eruptions, may also occur at volcanoes that are not presently active. Loss of life through volcanic activity has been rare in Nicaragua in the brief span of recorded history (~400 yr). Nevertheless, many volcanic eruptions that occurred during the past 6000 yr would be disastrous if they were to occur today. We emphasize that the frequency of potentially disastrous large volcanic eruptions is more than one per 1000 yr. Major disruption is inevitable in inhabited areas close to active volcanoes, especially where various kinds of volcanic flows are potentially major types of eruptive activity. The main factors determining volcanic risk in Nicaragua include:

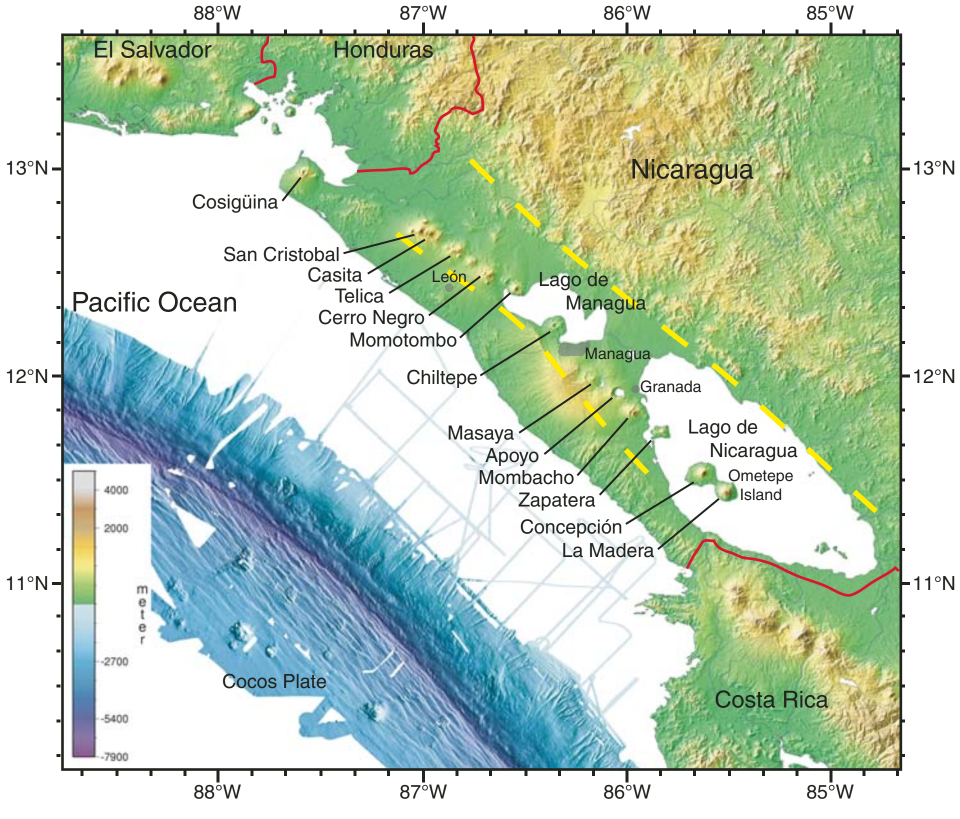

Figure 1. Map of western Nicaragua showing lakes Managua and Nicaragua within the NW-SE trending Nicaraguan depression (yellow dashed lines; Weinberg 1992), the deep-sea trench (violet colors) where the oceanic Cocos plate subducts beneath Central America, and the arc volcanoes parallel to, and ~200 km from, the trench. Volcanoes mentioned in the text are indicated.

- Forty percent of Nicaragua's population lives within, and close to, areas of many active volcanoes.
- The low elevation of the Nicaraguan depression favors extremely common interaction between rising magma and (ground)water. This can generate especially explosive and thus hazardous eruptions.
- Large Lake Managua, which forms the northern boundary of the city of Managua with several eruptive centers lying within the lake, as well as Lake Nicaragua to the south with the volcanoes Mombacho, Concepción, and Maderas, may be sites of highly explosive eruptions and tsunamis.
- The large spectrum of locations, magnitudes, and mechanisms of possible future eruptions presents a challenge for emergency planning. This is even more of a challenge because Nicaragua has also been victim to other disastrous natural events. Examples are the earthquakes that destroyed the capital, Managua, in 1931 and 1972, a tsunami that devastated the Pacific coast in 1992, and major storms, such as Hurricane Mitch in 1998, which triggered the disastrous lahar at Casita volcano.

Sometimes the eruption magnitude (e.g., the volume of material erupted) is equated with the degree of hazard or risk—in other words, the larger the eruption, the greater the hazard or risk. This correlation commonly does not hold, however, since other factors are more important. Increasing investment in communication, power lines, pipelines, transportation lines, etc., as well as the increasing complexity of such networks, have greatly increased vulnerability. The rising population density close to active volcanoes, not only in sprawling urban areas such as Managua and the nearby regions, but also in the agricultural areas in the Nicaraguan depression (Fig. 1), is a particularly acute factor of rising vulnerability. Volcanic and other types of natural disasters are certain to increase in the future because the degree of vulnerability of Nicaragua, as well as of societies worldwide, is rising rapidly.

In this review, we describe major types of volcanic hazards in general terms and illustrate each by a brief summary of case histories of well-studied volcanic events in Nicaragua and their impact on the environment. Discussions of large eruptions include our results from on-land and off-shore mapping of widespread pyroclastic deposits erupted during the past ~40,000 yr in west-central Nicaragua. Some results are included in Kutterolf et al. (2006), Freundt et al. (2006), Wehrmann et al. (this volume), and Pérez and Freundt (this volume). We group the volcanic hazards into three categories: (1) hazards from explosive eruptions; (2) hazards from nonexplosive activity; and (3) hazards from mass flows at volcanoes. We conclude by discussing several aspects of volcanic risk mitigation.

## VOLCANOES OF NICARAGUA

We will discuss types of volcanic eruptions and their hazards only briefly since these are treated more fully in current textbooks (Francis and Oppenheimer, 2004; Schmincke, 2004). There are basically four main types of volcanoes in Nicaragua, defined by their morphology, internal structure, eruption mechanism, and dominant magma composition.

### Stratocones

Most common and most impressive are large volcanic edifices called composite volcanoes or stratocones (Fig. 2B). They form the main backbone of the country from Cosigüina in the north to Concepción and Maderas on Ometepe island in the south. These volcanoes are complex in that they consist of intrusions, such as dikes and sills; extrusive lava domes and flows; several types of pyroclastic deposits (also called tephras), such as fallout, agglutinates, and deposits of pyroclastic density currents; and epiclastic deposits, including various types of breccias and mass-flow deposits, such as lahars (mud flows), extending far into the surrounding plains. The structural complexity of stratocones reflects their evolution by a wide range of eruptive mechanisms, intensities, and magnitudes, including highly explosive Plinian eruptions, and by volcanotectonic and mass-wasting processes. The dominant composition of these volcanoes is andesite. Studies of Nicaraguan stratocones include San Cristóbal (Hazlett, 1987) and Concepción (Borgia and van Wyk de Vries, 2003).

### Caldera Volcanoes

The second type of volcano forms broad, low edifices with shallow-dipping outer flanks and with a major, steep-walled subsided basin in the center called a caldera. Calderas are commonly filled with a lake and may be several kilometers in diameter, such as Apoyo (7 km in diameter, Fig. 2A; Sussman, 1985). Caldera volcanoes are the sites of particularly voluminous, highly explosive Plinian eruptions resulting in thick, widespread sheets of both pumice-fall deposits (Fig. 3A) and massive, ash-rich deposits of pyroclastic flows called ignimbrites. Eruptions of major pyroclastic flows are not common, but when they occur, they can cause widespread havoc because they are hot (often >500 °C), travel rapidly, and destroy everything in their paths. At subduction zones, the large-volume Plinian eruptions are commonly of silicic composition, mainly rhyolite and dacite. In Nicaragua, however, Masaya Caldera has repeatedly produced such large eruptions from mafic magmas (Williams 1983; Pérez and Freundt, this volume; Wehrmann et al., this volume).

### Scoria Cones

Scoria cones, rarely more than 200 m high, are especially common. They are generally of mafic composition, olivine-bearing basalt being most common. Scoria cones consist dominantly of fallout scoria blocks and lapilli and dikes and lava flows produced by Strombolian eruptions (Figs. 2D and 3B). Particularly vigorous Strombolian eruptions can form generally black layers of fallout lapilli and ash transported up to many kilometers from the scoria cone. The most prominent and active scoria cone in

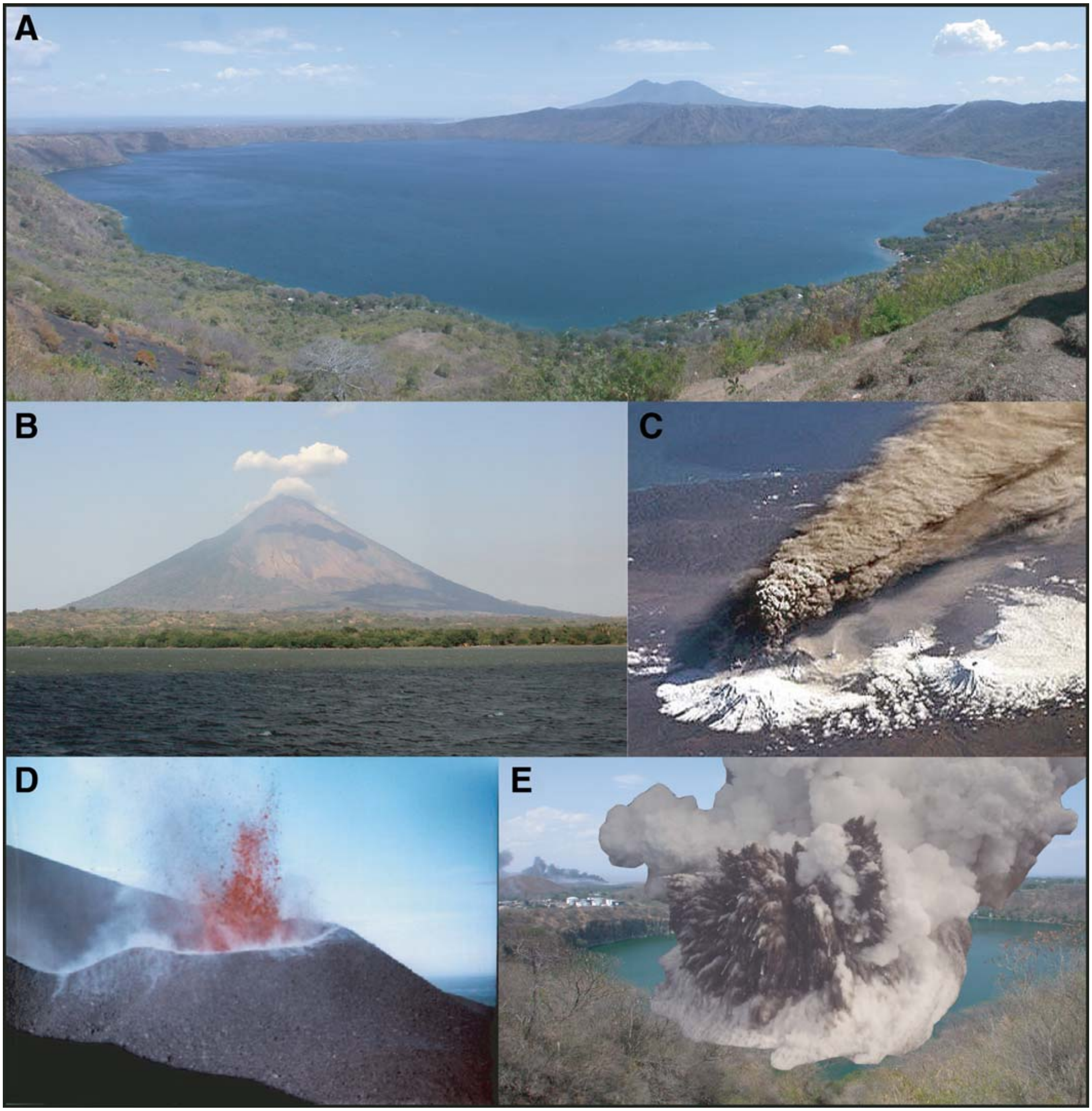

Figure 2. (A) Apoyo caldera with Mombacho stratocone in the background. (B) Concepción stratocone. (C) 15–20-km-high eruption column advected sideways by the wind and producing a widespread fallout deposit. Kliuchevskoy, Kamchatka, 1994. U.S. National Aeronautics and Space Administration Space Shuttle STS-068 photograph. (D) Small Strombolian eruption of Cerro Negro in 1995. Photograph from Instituto Nicaragüense de Estudios Territoriales. (E) Asososca maar in western Managua with superimposed image of phreatomagmatic eruption ejecting dark jets of pyroclastic debris (from Fukutoku-Okanoba volcano 1986, Japan; Hydrographic and Oceanographic Dept., Japan coast guard, www1.kaiho.mlit.go.jp.). Note refinery near crater.

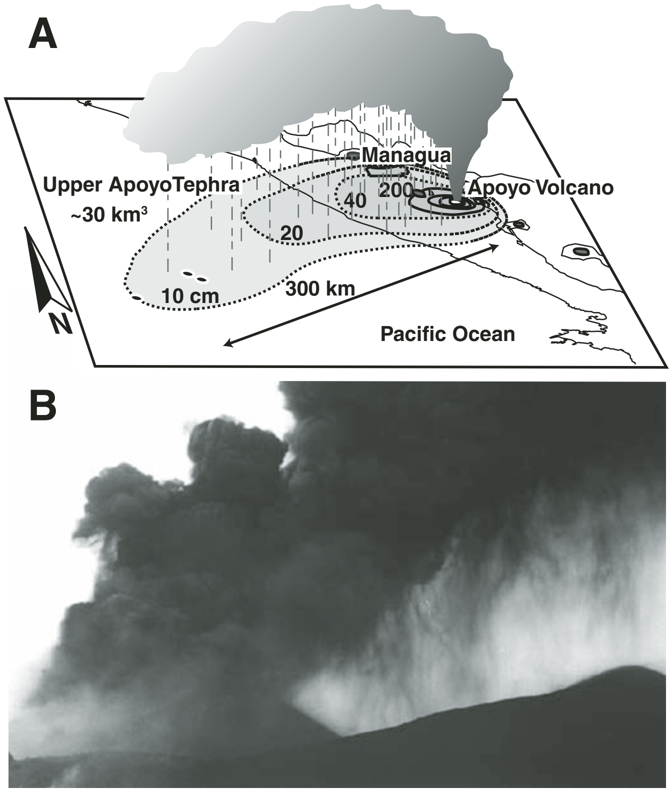

Figure 3. (A) Illustration of fallout from a westward-driven Plinian ash cloud from an eruption of Apoyo volcano ~25,000 yr ago, generating a tephra blanket covering an area of 50,000 km$^2$ with >10 cm thickness (Upper Apoyo Tephra). Contours (isopachs) of tephra thickness (cm) are indicated. (B) Ash raining out of the ash cloud of the 1995 Cerro Negro Strombolian eruption. Photograph from Instituto Nicaragüense de Estudios Territoriales, Managua.

Nicaragua is Cerro Negro (McKnight and Williams, 1997; Hill et al., 1998; La Femina et al., 2004). Young scoria cones also occur in western Managua and near Granada (Ui, 1972; Walker, 1984).

### Maar Volcanoes

When magma interacts with groundwater or surface water, the magma is quickly quenched, while the water is explosively vaporized, resulting in phreatomagmatic eruptions. The volcanic landform so generated is a maar, a crater with steep to vertical walls, generally <1 km in diameter, and often filled with a lake (Fig. 2E). A maar is surrounded by a ring of well-bedded deposits that may largely consist of fragments of country rock shattered by the explosive vaporization of the external water. Most maars form from basaltic magma, such as the prominent Asososca and Nejapa maars along the Nejapa-Miraflores alignment and Tiscapa maar in Managua city. Laguna Xiloá on Chiltepe peninsula is a maar that erupted dacitic magma. Masaya Caldera is a complex basaltic volcano in that it also comprises maar-type structures, its eruptions alternating between pyroclastic eruptions and lava flows and major phreatomagmatic eruptions (McBirney, 1956; Walker et al., 1993; Pérez and Freundt, this volume). Dominantly Plinian eruptions from stratocones or calderas often also include phreatomagmatic eruption phases.

## HAZARDS FROM EXPLOSIVE ERUPTIONS

The extent of hazards from volcanic eruptions depends on the eruption style and the mass of magma discharged. Explosive volcanic eruptions disperse pyroclastic material as fallout from eruption columns spreading with the wind and/or as deposits from pyroclastic density currents moving along the ground. Non-explosive eruptions produce basaltic lava flows (e.g., Masaya) or highly viscous dacitic lava domes (e.g., Santiaguito, Guatemala), which episodically collapse to form hazardous pyroclastic flows. Fortunately, such flows have not occurred at Nicaraguan volcanoes during their recent history.

### Pyroclastic Fallout

Most of the magma volume erupted during explosive volcanic eruptions in Nicaragua during the past ~40,000 yr was deposited as fallout from eruption columns that were injected ~15–40 km up into the atmosphere and then were transported laterally by the prevailing wind (Fig. 2C). Figure 3A illustrates the ash dispersal to >300 km during a Plinian eruption from Apoyo caldera 25,000 yr ago, the biggest eruption in Nicaragua's recent volcanic history. The area affected by fallout depends primarily on the height of the eruption column, which in turn depends on the thermal mass flux of the eruption. Compared to the Apoyo eruption, Cerro Negro volcano has produced numerous (at least 22) but small eruptions since its birth in 1850 (McKnight and Williams, 1997; Hill et al., 1998). The Strombolian eruptions of Cerro Negro formed lava flows, lava fountains of coarse spatter building the cone (Fig. 2D), and higher ash plumes, such as the one in Figure 3B of the 1995 eruption. Though relatively small, a similar but larger eruption in 1992 covered the city of León, some 20 km west of the volcano (Fig. 1), with an ash blanket 4 cm thick that caused some roofs to collapse. At least two people were killed and 146 injured; crops and infrastructure worth $19,000,000 were destroyed (Connor et al., 2001).

Wind directions change with height in the atmosphere and with the season of the year (Fig. 4). The main direction of fallout dispersal thus depends on the height of the eruption column and the season. Ash from either <5-km-high Strombolian or >20-km-high Plinian eruptions will most probably be dispersed westward from the volcano. Dispersal directions can be more variable for eruption columns of intermediate height, with westerly directions prevailing from June to September but northeasterly directions for the remaining year (Fig. 4B). Southerly regions a few kilometers from the vent (depending on eruption size) are least affected by fallout.

Here we are mainly concerned with Plinian eruptions that are characterized by large thermal mass flux and produce

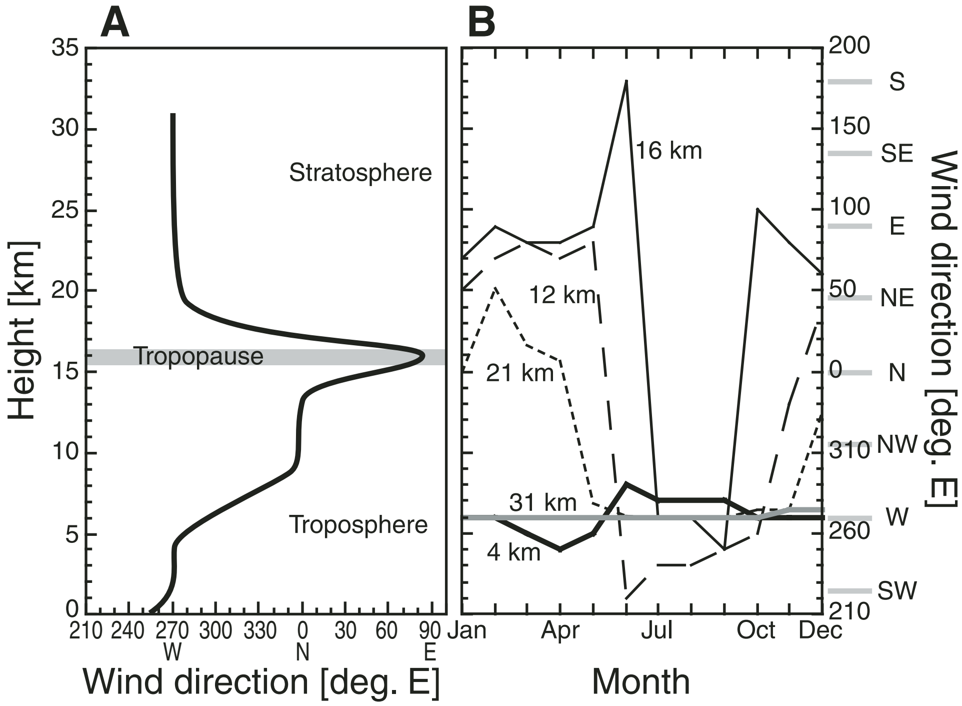

Figure 4. Present-day wind directions in Nicaragua. (A) Annual average wind direction versus atmospheric height above ground. (B) Monthly averages for selected heights. In meteorology, wind direction is noted as where the wind is blowing from; here we show the direction it is blowing to for easier comparison with tephra dispersal directions. Data from the U.S. National Oceanic & Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences Climate Diagnostics Center, www.cdc.noaa.gov.

eruption columns reaching high into the stratosphere (i.e., more than 15 km). While such large-magnitude eruptions occur much less frequently, areas affected by their associated hazards are many orders of magnitude larger than for Strombolian eruptions. Almost all of west-central Nicaragua would, in fact, be affected by a Plinian eruption from any of the potential vents in the area. Plinian eruptions are typically produced by magmas of silicic compositions, but in Nicaragua basaltic magmas from the Masaya volcanic system also generated such eruptions (Wehrmann et al., this volume; Pérez and Freundt, this volume).

We mapped the areal thickness and grain-size distributions of the deposits from past Plinian eruptions at Apoyo and Masaya calderas and the Chiltepe volcanic complex (Fig. 1), including Apoyeque stratocone and Xiloá maar. Data from such maps allows us to estimate erupted masses and column heights. The 15–30-km-high ash clouds from these eruptions were driven by the wind mostly to the west or northwest, gradually losing their load of ash and lapilli to form fan-shaped blankets of tephra on the ground, covering areas on the order of $10^3$ to $10^4$ km$^2$ and >10 cm in thickness (Fig. 3A). The magnitudes of these eruptions, $M = \log_{10}(m_e) - 7$, where $m_e$ is the erupted mass in kilograms (Pyle, 2000), range from 4.3 to 6.3 (i.e., over two orders of magnitude). For comparison, magnitudes of the well-known Mount St. Helens 1980 (USA) and Mount Pinatubo 1991 (Philippines) eruptions are 4.8 and 6.0, respectively (Pyle, 2000). The largest magnitude, $M = 7.3$, of a historical eruption was reached by Tambora volcano, Indonesia, in 1815.

The impacts of large blocks ejected ballistically from a crater or falling out of the lower part of an eruption column are limited to a few kilometers from the vent. A major hazard from pyroclastic fallout that can extend to great distances from the volcano is the partial to total collapse of buildings that become heavily loaded with ash. At least partial building collapse is to be expected when the load pressure exceeds ~1 kPa (Pyle, 2000). Ash that is wet (from eruption or soaked with rain) exerts 1.5 times the load stress of dry ash of the same thickness. Collapse may occur at even lower loads where load stress is focused at the fixings of pole-supported roofs rather than distributed along walls. Probabilities of roof collapse under given ash load for a range of designs have been determined for some volcanic regions (Spence et al., 2005) but are not yet available for Nicaragua. The destructiveness index $D = \log_{10}(A)$, where $A$ is the area [m$^2$] over which ash accumulation exceeds 1 kPa (~10 cm thickness), ranges from $D = 2.8$ to 4.0 for the Nicaraguan Plinian eruptions. For comparison, $D = 2.9$ and 3.4 for the Mount St. Helens and Pinatubo cases, and the largest recorded value of $D = 4.5$ is from the Taupo 186 A.D. eruption, New Zealand (Pyle, 2000).

One way to estimate the possible impact of future fallout on west-central Nicaragua is to consider the average effect of past eruptions. The average thickness of tephra deposited at a particular locality from a past large eruption is obtained by dividing the total tephra thickness locally accumulated (Fig. 5B) by the number of eruptions that contributed to each locality over a period of time. Figure 5C shows the average thickness based on the past ~40,000 yr, while the average thickness in Figure 5D is based on the past 6000 yr. The resulting distribution pattern is quite different from that of a single eruption (Fig. 3A) because the three potential source volcanoes (Chiltepe, Masaya, Apoyo) are considered

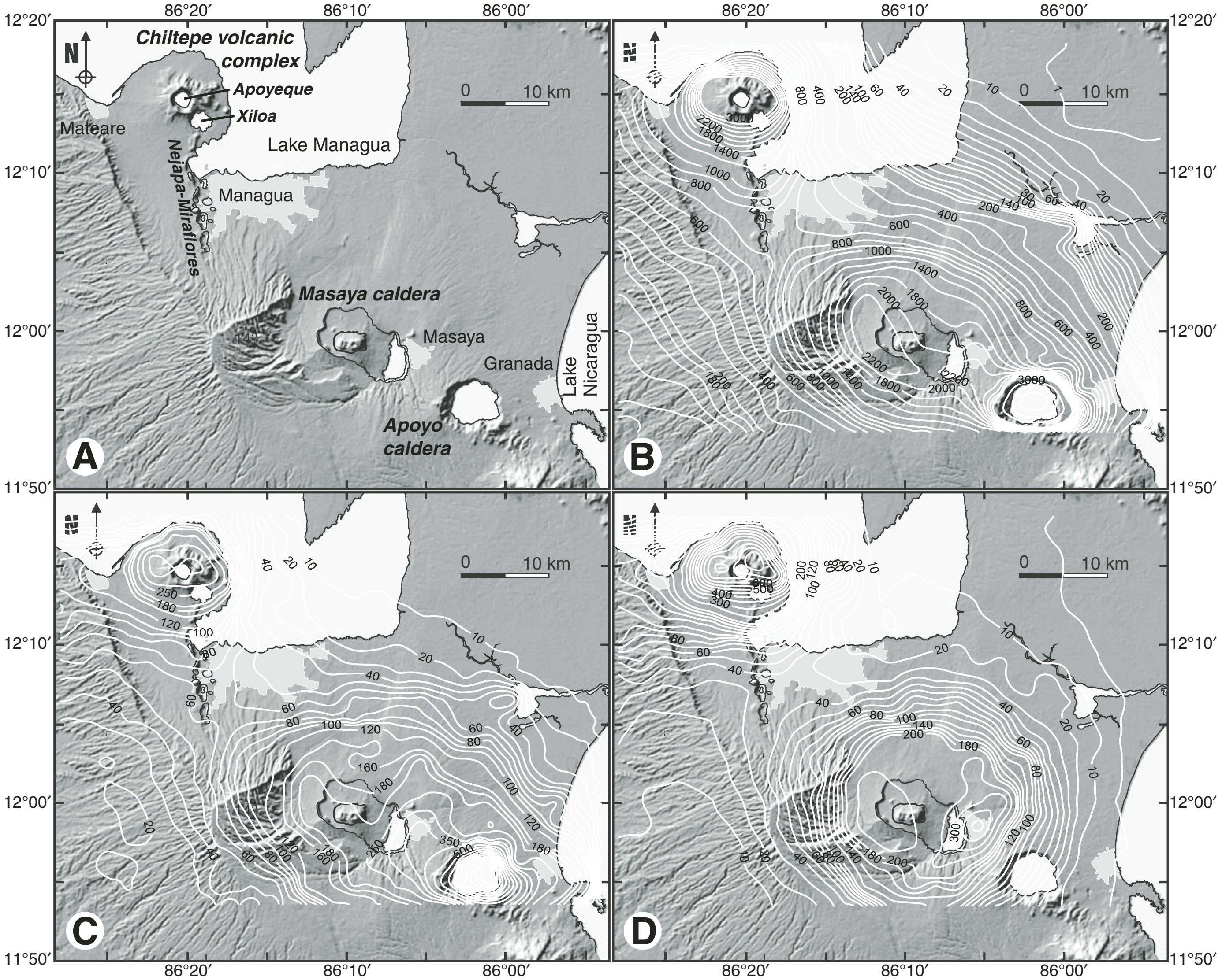

Figure 5. (A) Locations on the digital elevation model relief of the area around Managua. (B) Isopach map of the total accumulated thickness (cm) of all widespread fallout deposits formed during the past ~40,000 yr (see Fig. 7A). (C) Average fallout thickness per eruption (total accumulated thickness divided by number of eruptions represented at each locality) emplaced by eruptions during the past ~40,000 yr. (D) Average thickness of fallout per eruption based on the eruptions of the past 6000 yr only.

simultaneously without taking into account the probability of a future eruption at any of them, a topic that is discussed below in the section on eruption recurrence. The map shows, however, that all of west-central Nicaragua is potentially threatened by destructive fallout accumulating to a thickness of more than 10 cm.

Volcanic ash fallout also creates hazards other than structural collapse. The inhalation of very fine (<10 µm) ash particles can cause respiratory problems for days after an eruption (Baxter, 2000). Ground traffic will be inhibited by very low visibility, and engine air filters will be clogged with ash. Air traffic will also be inhibited. In the 1990s, 12 eruptions worldwide caused damage to or failure of turbines on aircraft even several hundred kilometers away from the volcano (Miller and Casadevall, 2000).

## Pyroclastic Density Currents

Pyroclastic density currents are hot mixtures of pyroclastic debris and gas that move along the ground. They form during explosive eruptions by partial or total collapse of an eruption column too dense to ascend higher into the atmosphere, or by direct ejection from the crater. They also form by partial collapse of extruding lava domes, but such flows (called block-and-ash flows) are not considered here since they have not been recorded in Nicaragua. The volume, runout distance, and flow behavior of pyroclastic density currents can vary widely. Two types of pyroclastic density currents are commonly distinguished: (1) pyroclastic flows consisting of a high concentration of ash form massive deposits (ignimbrites), and (2) gas-rich, highly turbulent pyroclastic surges that typically leave wavy, stratified deposits with dune structures (Freundt et al., 2000; Valentine and Fisher, 2000). Pyroclastic flows are more strongly confined to valleys, while pyroclastic surges can spread across valley shoulders. Large-volume pyroclastic density currents of any form, however, can spread across the entire landscape.

All types of flows pose the greatest hazards to communities. People tend to live in valleys fertilized by volcanic soil with nearby water resources. These valleys are also the favored pathways of volcanic flows. The main loss of lives (47% in 1900–1986; Blong, 1996) and the largest economic losses in the past century from volcanism resulted from pyroclastic flows and surges. Pyroclastic density currents are particularly dangerous phenomena of explosive volcanic eruptions for three reasons: (1) their occurrence during an eruption is sudden and unpredictable, and they spread very rapidly (10–150 m/s), allowing for extremely short warning times; (2) their high temperatures (several hundred degrees Celsius) and magmatic gases are lethal; and (3) they have enormous destructive power, virtually destroying everything in their path. The dynamic pressure such currents exert on the upstream face of buildings is $P=\frac{1}{2}\rho u^2$, where $\rho$ is the bulk density of the pyroclast-gas mixture and $u$ is the velocity of the current. Hence, a pyroclastic flow with 40 vol% pyroclasts moving at 15 m/s has the same destructive potential ($P \approx 50$ kPa) as a pyroclastic surge with only 1 vol% pyroclasts but racing at a speed of 100 m/s. Pyroclastic density currents typically develop dynamic pressures of 1–1000 kPa, and 20 kPa is already sufficient to inflict severe to total damage on most buildings (Valentine, 1998).

In Nicaragua, pyroclastic flows formed during a Plinian eruption from Apoyo caldera ~25,000 yr ago inundated the low-lying areas between Apoyo and Mombacho to the south and around Granada to the east (where they entered Lake Nicaragua), leaving 8 km$^3$ of massive ignimbrite reaching >20 m thickness (Sussman, 1985). Several pyroclastic flow deposits of yet unknown age form widespread sheets on the plains west and northeast of Momotombo volcano (Hradecky, 2001). A ~20 m thick ignimbrite, erupted only 34,000 yr ago from an unknown source at the volcanic arc, covers the plains descending toward the Pacific west of Jinotepe (our observation and $^{14}$C dating). The most recent Nicaraguan eruption producing voluminous pyroclastic flows occurred in the very north at Cosigüina in 1835 (Self et al., 1989; Scott et al., this volume); the deposits cover large parts of the peninsula, and large amounts of ash were shed into the surrounding sea. All these pyroclastic flows filled valleys but were voluminous enough to also flood large plains.

Pyroclastic surges were associated with virtually each of the Plinian eruptions, although most did not reach farther than ~3 km from vent. They formed either by collapse of the Plinian eruption columns or by phreatomagmatic phases of these eruptions. A spectacular example is the coarse-pumice surge deposits exposed on the rim of Apoyo caldera, which were produced during the terminal phase of the last Apoyo eruption ~25,000 yr ago. The Plinian Chiltepe eruption from Apoyeque stratocone less than 2000 yr ago generated surges reaching >5 km from the crater, and phreatic explosions (driven by magmatic heat but without ejection of new magma), producing smaller surges, probably continued for months after the main Plinian eruption, building a tuff-ring on the rim of Apoyeque crater.

Pyroclastic surges are an integral part of phreatomagmatic eruptions, which are discussed in the next section. Such surges spread radially around the vent and can initially have supersonic velocities. The largest phreatomagmatic surge deposit known in Nicaragua, the <2000 yr old Masaya Tuff (Pérez and Freundt, this volume), has spread near-radially up to 40 km around Masaya caldera.

Pyroclastic surge deposits commonly are the accumulated sediment from numerous successive surge flows, each leaving a deposit that may be only a few dm to cm thick. These change from dune-bedded to laminated ash deposits while exponentially thinning away from vent. Distal laminated ashes mainly represent fallout from drifting ash clouds remaining after a surge has lost most of its pyroclast load and kinetic energy. The dune-bedded deposits, however, mark the minimum area over which the surge moved rapidly and was highly destructive. These areas are indicated in Figure 6 and form an almost continuous ~20-km-wide zone along the 80 km length of the volcanic arc from Granada through Masaya and west-Managua to north of Mateare.

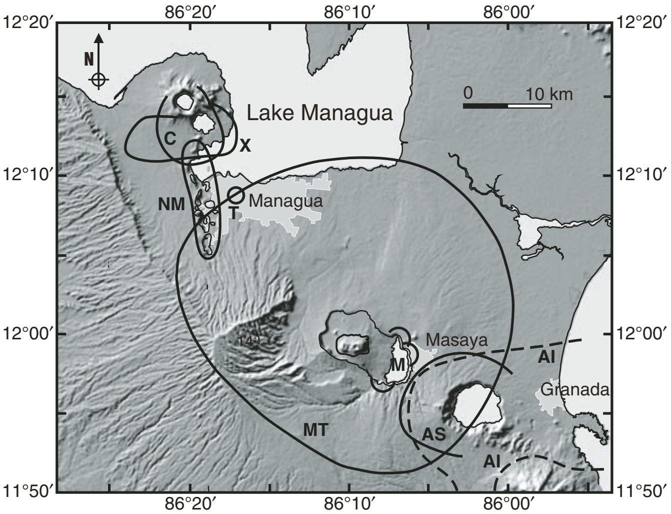

Figure 6. Outline of areas that suffered severe to total destruction by pyroclastic density currents during past eruptions. C—surges of Chiltepe Tephra eruption; X—Xiloá surges; NM—Nejapa-Miraflores maars; T—Tiscapa maar; MT—Masaya Tuff (25-cm isopach from Pérez and Freundt, this volume); M—small phreatomagmatic eruptions in SE part of Masaya caldera; AS—Apoyo surges; AI—Apoyo ignimbrite (dashed line; after Sussman 1985) of Upper Apoyo Tephra. Solid lines approximately outline areas where surge deposits are cross-bedded; lower-energy flow occurred beyond these limits. See Figure 5A for localities.

## Recurrence of Large Eruptions

Periods of quiescence, particularly between large-volume eruptions, last much longer than the few hundreds of years of recorded human history in Nicaragua. Assessment of the probability of occurrence of another such eruption has to rely on extrapolation of the past record of activity of the volcanoes, assuming that the past behavior continues into the future. This approach requires careful mapping, stratigraphic subdivision, dating, and volcanological interpretation of the older volcanic deposits. Here we focus on Masaya caldera and the Chiltepe peninsula—a volcanic complex hosting Apoyeque stratocone, Xiloá maar, and other now hidden vents—for which we have the most complete data on their eruptive histories. Apoyo caldera experienced two Plinian eruptions ~25,000 yr ago separated by a relatively short period of time (perhaps a few hundred years; Fig. 7A), but little is yet known of its earlier history.

A simple way to estimate the time frame for a future eruption is to assume that a volcano follows a periodic pattern; the period is obtained by dividing the time over which a volcano was active by the number of eruptions that occurred. Masaya caldera produced four large eruptions during the past <6000 yr,

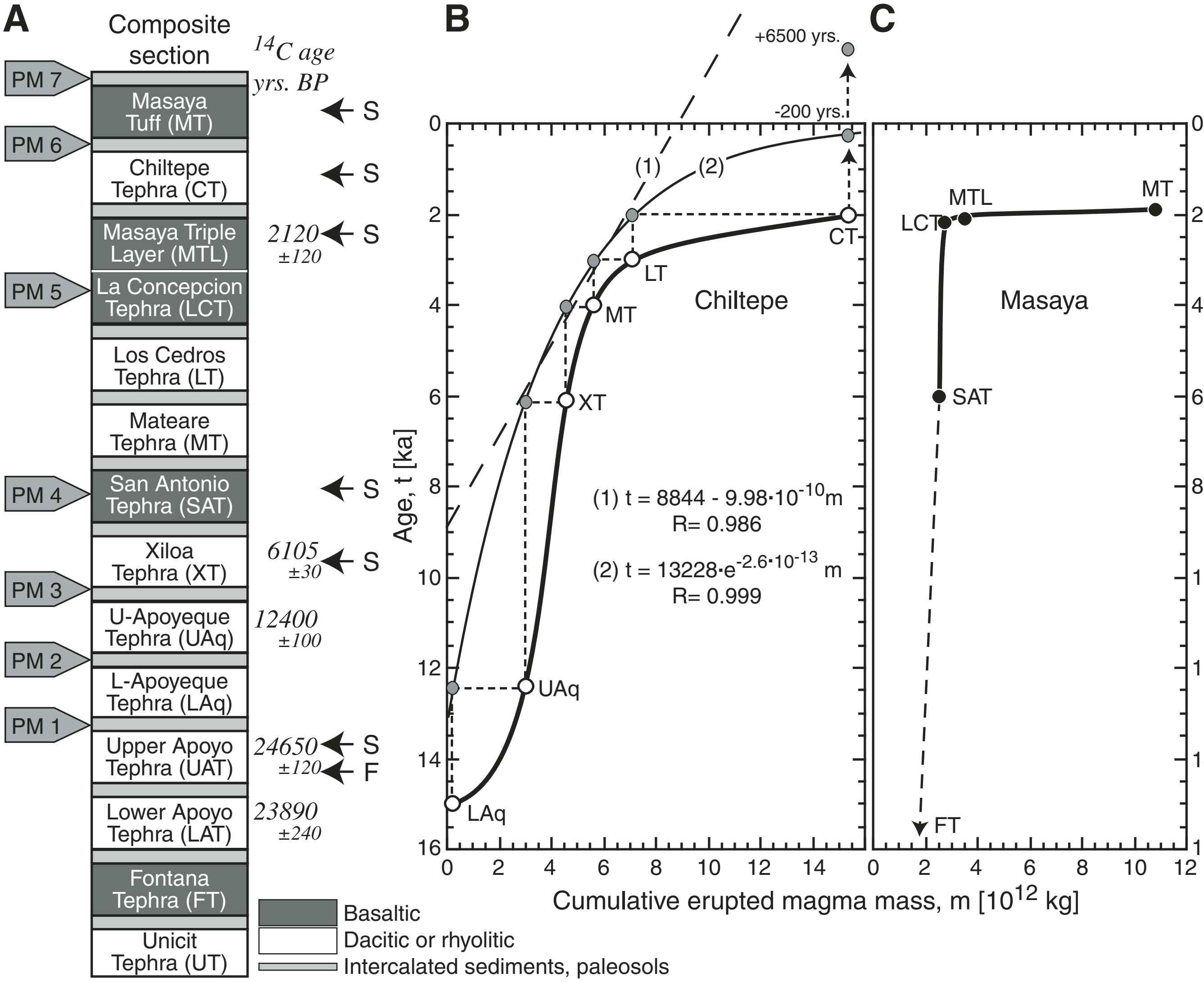

Figure 7. (A) Composite stratigraphic succession of deposits from highly explosive eruptions in west-central Nicaragua. Arrows at right indicate the production of pyroclastic surges (S) and pyroclastic flows (F) during these eruptions. Gray arrows at left mark the stratigraphic position of major phreatomagmatic (PM) eruption phases along the Nejapa-Miraflores lineament, in Managua city, and along the southwestern shore of Lake Managua. Our age data were determined by the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research at Kiel University. (B) Cumulative mass of erupted magma versus eruption age for the Chiltepe volcanic complex. Ages of undated tephras are guessed considering the nature of intercalated deposits. (1) and (2) are linear and exponential regressions, respectively, through the gray dots as explained in the text. (C) Cumulative mass of erupted magma versus eruption age for the Masaya caldera.

indicating an average recurrence period of <1500 yr. Over a similar period of time of 6100 yr, four eruptions were also produced at the Chiltepe volcanic complex, giving a similar average recurrence period. Another simple assumption is that a volcano is characterized by an average eruption magnitude. Dividing the mean ejected magma mass per eruption at Chiltepe by the long-term average mass production rate yields an average recurrence interval of ~1500–2500 yr, considering the past 6100 or 15,000 yr, respectively. For the past 6000 yr at Masaya caldera, the analogous calculation yields ~1200 yr. The last events at both volcanoes, the large phreatomagmatic Masaya Tuff eruption and the Plinian Chiltepe Tephra eruption (Fig. 7A), occurred less than 2000 yr ago. However, both these simple assumptions are poorly constrained here, although they seem quite reasonable in other cases (e.g., at Cerro Negro; Hill et al., 1998).

A more detailed impression of how a volcanic system evolved can be gained from the pattern in which erupted magma mass accumulated with time through a series of eruptions. Using the Chiltepe complex as an example, the white dots in Figure 7B are the cumulative erupted magma mass (added up starting from the Lower Apoyeque Tephra, Fig. 7A) plotted at the age of each respective eruption (we guessed some ages since absolute age data are incomplete). The gray dots are the same cumulatives masses projected upward to the age of the respective next eruption. If eruptive activity at Chiltepe is controlled by a steady process (e.g., steady extension of the Nicaraguan depression), then the gray dots should lie on or close to a straight line (Bacon, 1982; Wadge, 1982). Line (1) in Figure 7B is a linear regression through the Xiloá Tephra (XT) to Los Cedros Tephra (LT) data. A better fit, however, is obtained for an exponential regression using all data (Lower Apoyeque Tephra [LAq] to LT), yielding line (2) in Figure 7B. This would imply that whatever process controls eruptive behavior at Chiltepe is not linear but exponentially accelerating. A forecast of the next future eruption can be made by projecting the cumulative erupted mass of the last eruption (Chiltepe Tephra [CT]) up to either line (1) or (2). For the exponential regression, the next eruption should already have occurred ~200 yr ago, whereas it would be expected in 6500 yr for the linear regression (Fig. 7B). Clearly, a more useful forecast requires a better understanding of the processes that control the evolution of the Chiltepe volcanic complex, which has only produced eruptions of magnitude $M > 4$ during the past few thousand years and is likely to continue doing so.

The data for Masaya caldera (Fig. 7C) comprise three moderately large eruptions (San Antonio Tephra [SAT], La Concepción Tephra [LCT], Masaya Triple Layer [MTL]; Fig. 7A), the unusually large Masaya Tuff eruption (MT), and a long repose period of ~30,000 yr back to the Fontana eruption (which actually occurred outside the caldera; Wehrmann et al., this volume). The large variations in magnitudes and recurrence periods within this small amount of data do not allow for extrapolation analogous to Chiltepe. Post-caldera volcanic activity since the last large eruption from the Masaya caldera has been cone-forming Strombolian and phreatomagmatic activity and lava effusion (Walker et al., 1993), none of which was very hazardous outside the caldera. This may indicate that the Masaya magmatic system has been reduced to a state favoring less hazardous volcanism, but it does not exclude the possibility that the system may return to a state of much higher activity.

## Magma-Water Interaction

Most of Managua is built on volcanic deposits whose mode of eruption was largely determined by explosive interaction of magma with groundwater or surface water, as clearly demonstrated by the maars of Tiscapa, Asososca, and Nejapa in the city (Fig. 8). The abundance of phreatomagmatic eruptions is not surprising since Managua is situated in the Nicaragua depression, a large catchment area of water as evidenced by the two large lakes (Fig. 1). This environmental setting facilitates the access of water to the magmatic systems in this depression. Phreatomagmatic eruptions from vents along the Nejapa-Miraflores lineament west of Managua and reaching north up to Chiltepe peninsula discharged juvenile magma precooled by mixing with water and lithic material, and hence had a low thermal mass flux and produced ~3 km diameter tuff rings around the vents with only little ash fallout to greater distance. The well-stratified tuff-ring deposits (Fig. 9) were formed by fallout, surges, and debris jets (Fig. 2E) discharged by numerous very powerful explosions.

Little is yet known about the chronology of these phreatomagmatic eruptions. Our preliminary results, based on some of the widespread Plinian pumice layers being intercalated with the tuff-ring deposits (Fig. 9), show that at least seven phases of phreatomagmatic activity occurred from more than 13,000 yr to less than 2000 yr ago (Fig. 7A) and are thus likely to continue in the future. Eruptions from this zone, although small in a global context, would be extremely disastrous because of the high population density and industrialization in western Managua.

## Eruption-Triggered Tsunamis

Tsunamis, waves formed by sudden displacement of a large water volume, are infamous for their occurrence in the oceans. Notable examples are the disastrous events in 2004 in the Indian Ocean or the 1992 tsunami that struck the Pacific coast of Nicaragua. Less well known is the fact that tsunamis also occur in lakes. Lake tsunamis can be triggered by volcanoes in several ways (Beget, 2000; Freundt, 2003): by volcanic earthquakes; by underwater eruption and phreatomagmatic explosions; and by entrance of pyroclastic flows, lahars, or debris avalanches. The debris avalanche of 18 May 1980 at Mount St. Helens entered Spirit Lake and caused a tsunami that ran up the shore to 260 m above the lake level (Voight et al., 1981). Flank-collapse avalanches from Mombacho entered Lake Nicaragua and probably triggered tsunamis. The pyroclastic flows generated during the Upper-Apoyo eruption ~25,000 yr ago also entered Lake Nicaragua and may have triggered tsunamis, as did the flows of the 1883 Krakatau eruption entering the Java Sea at Indonesia (Carey et al., 2001).

Phreatomagmatic explosions that occurred in Xiloá maar, which lay under shallow water at the time of eruption (Freundt et al., 2006), and at vents hidden in Lake Managua, which produced the thick phreatomagmatic deposits along the southwestern lake shore, also had the potential to trigger tsunamis like those witnessed during explosive eruptions at Lake Karymskoye, Kamchatka, in 1996 (Belousov et al., 2000). Another place in Nicaragua where volcanogenic tsunamis can be generated is Cosigüina peninsula at the Gulf of Fonseca, an inlet of the Pacific Ocean. A tsunami generated there could spread over the gulf within minutes and affect not only the villages on the Nicaraguan and Honduran coasts but also the relatively large town of La Union in El Salvador.

Fortunately, in Nicaragua, the size of lake tsunamis would be limited by the shallow depths of Lake Managua (<26 m) and Lake Nicaragua (<70 m). Tsunami deposits related to the above-mentioned events have not yet been identified. However, we have recently documented a tsunami deposit intercalated with the Mateare Tephra (Fig. 7A) that was erupted from a vent near the northwestern shore of Chiltepe peninsula between 3000 and 6000 yr ago (Freundt et al., 2006). The tsunami deposit is a sand layer (MS in Fig. 10) that was emplaced during the initial phase of the eruption, which consisted of discrete explosive eruption pulses (unit A in Fig. 10). The detailed mechanism of tsunami formation remains unknown, but tsunami formation apparently terminated when the eruption assumed a steady Plinian character (unit B in Fig. 10). The areal distribution of the sand layer suggests that the tsunami waves flooded inland to elevations of ~20 m above the lake level at the time of eruption.

Once formed, tsunamis travel away from their source at a velocity $c = \sqrt{gD}$ only depending on water depth, $D$, and acceleration due to gravity, $g$. Tsunami speed in the ocean is typically several hundred kilometers per hour. In the shallow Nicaraguan lakes, the velocity would be ~25–50 km/h. Considering the shore-to-shore distances, however, this means there would be less than an hour—and in most situations only minutes—of warning time. It is important to realize that volcanogenic lake tsunamis are a serious hazard along the shores of the two Nicaraguan lakes.

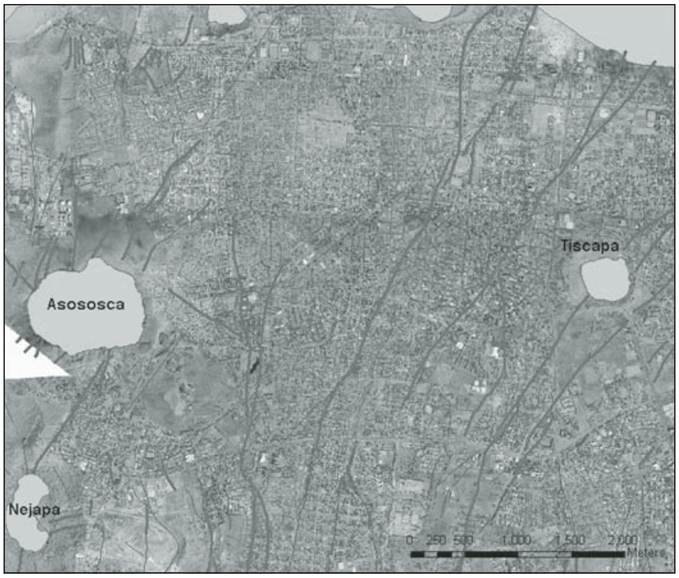

Figure 8. Aerial photograph of western Managua including the maars of Tiscapa, Asososca, and Nejapa. Thick gray lines are tectonic faults. From Instituto Nicaragüense de Estudios Territoriales, Managua.

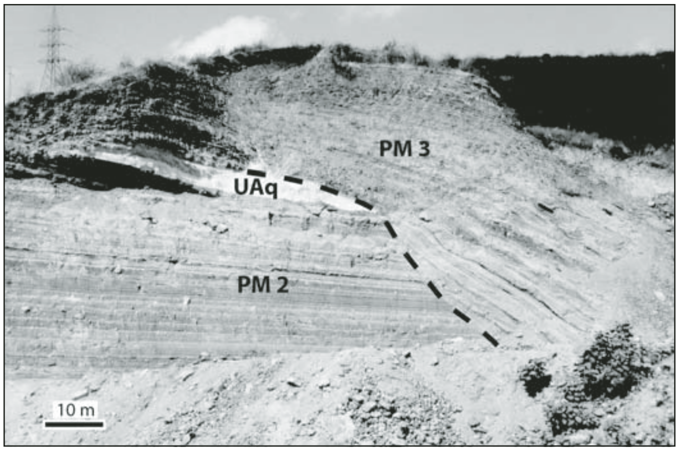

Figure 9. Two gray stratified phreatomagmatic units (PM2 and PM3 of Fig. 7A) separated by the intercalated white Upper Apoyeque Tephra (UAq; 12,400 yr B.P.) and an erosional unconformity (dashed line). Quarry in northwestern Managua city.

## HAZARDS FROM NONEXPLOSIVE ACTIVITY

### Lava Flows

Lava flows do not generally pose a direct hazard to people because they advance relatively slowly. Nevertheless, lava flows can cover major stretches of cultivated or inhabited land and destroy buildings and infrastructure. Long lava flows were erupted from Masaya volcano ~10 times during the past 500 yr. These include the 1772 lava, the longest lava flow (16 km) erupted in Central America during historic times (Pérez, 1993). Long lava flows also formed between 1527 and 1529 from the Maribios Range, comprising the volcanoes San Cristobal, Telica and Las Pilas (de Oviedo, 1855). The lava flow of the 1995 eruption of Cerro Negro volcano reached a distance of 2.5 km within a few days. Other major lava flows extruded from Momotombo volcano in 1886 and 1905 (Sapper, 1925; Gaceta Oficial de Nicaragua, 1886). Such lava flows are a risk for the geothermal power plant at the foot of this volcano.

### Volcanic Gases

Hot and toxic gases are an integral part of hazards associated with volcanic activity. Gases emitted by large-magnitude eruptions are known to affect local and global climate and atmospheric

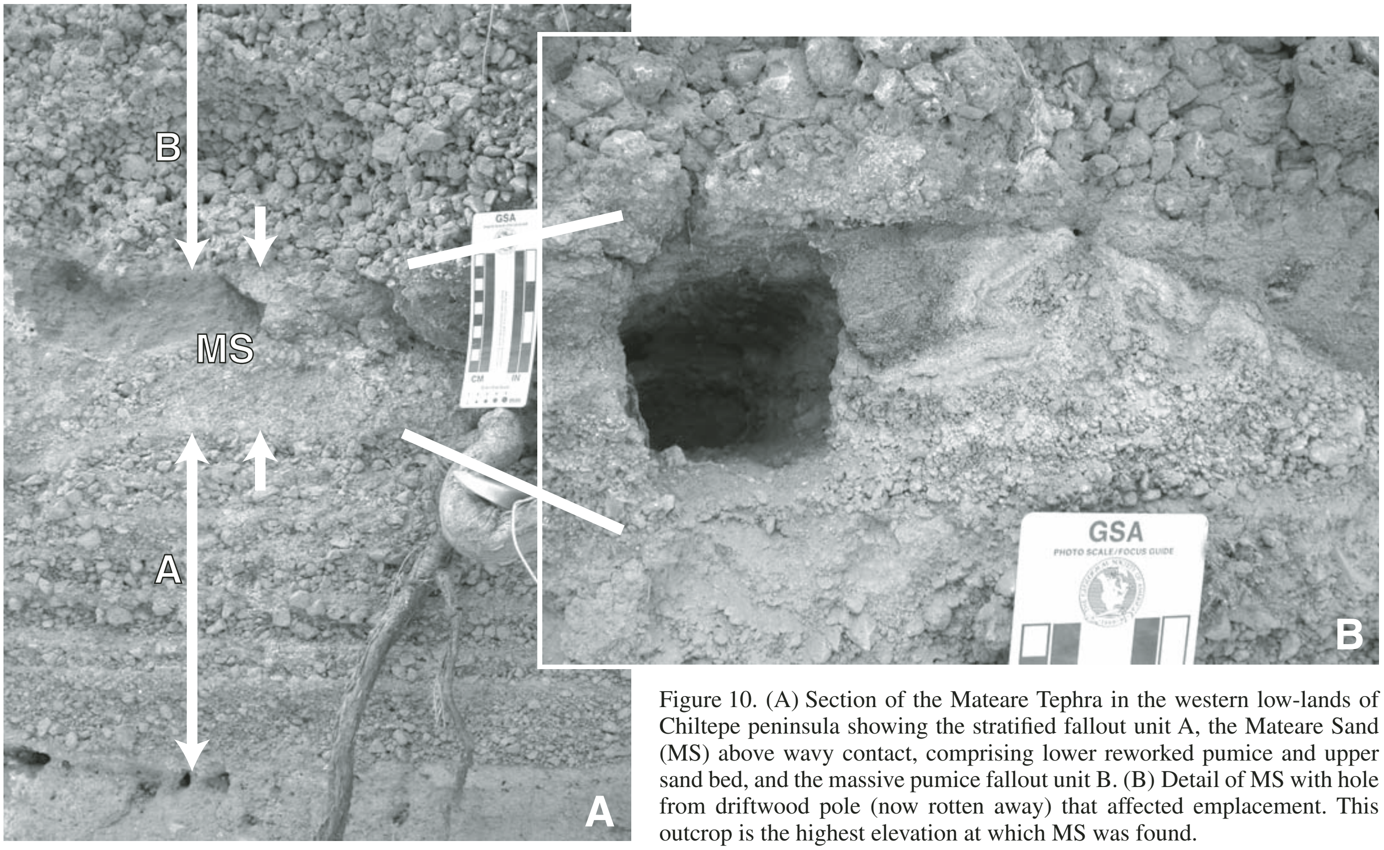

Figure 10. (A) Section of the Mateare Tephra in the western low-lands of Chiltepe peninsula showing the stratified fallout unit A, the Mateare Sand (MS) above wavy contact, comprising lower reworked pumice and upper sand bed, and the massive pumice fallout unit B. (B) Detail of MS with hole from driftwood pole (now rotten away) that affected emplacement. This outcrop is the highest elevation at which MS was found.

chemistry for years. However, large amounts of volcanic gases are not only released by magma degassing at depth during eruptions but also from open vents and fumaroles during repose periods between eruptions, which may last several decades. Steam mixed with sulfur dioxide ($SO_2$), carbon dioxide ($CO_2$), and many other components such as fluorine, chlorine, and bromine are continuously emitted from open vents and fumaroles, and, in sufficient quantities, may pollute air, water, and soil over hundreds to thousands of km$^2$ downwind from a volcano. Such gas plumes can affect human and animal health and destroy cultivated and natural crops, particularly in areas suffering long-term exposure due to steady wind direction. Permanent open vent and fumarole degassing in Nicaragua releases some 1500 metric tonnes/day (t/d) of sulfur dioxide that pollute the environment downwind from volcanoes (Andres and Kasgnoc, 1998; our data). In the long run, this is one to two orders of magnitude larger than the long-term average sulfur flux from explosive eruptions. The permanent gas plumes of Masaya and San Cristóbal volcanoes (Fig. 11) are the most prominent examples.

The three largest continuous emitters of volcanic gases in Nicaragua are Masaya, San Cristóbal, and Telica volcanoes (Duffell et al., 2003; Andres and Kasgnoc, 1998; our data). Each currently releases several hundred t/d $SO_2$. The large amount of $SO_2$ released into the atmosphere by these volcanoes produces volcanic air pollution, manifested by poor air quality, hazy atmospheric conditions, and acid rain. During the 1990s, the $SO_2$ emission rates for two of the three volcanoes fluctuated significantly and included periods with anomalously high gas emission rates (“gas crisis”). During such gas crises, one single volcano may produce more $SO_2$ than all other Nicaraguan volcanoes combined. $SO_2$ emission rates exceeding 3000 t/d were measured at Masaya on a few days in February–April 1998 and February–March 1999 (Duffell et al., 2003), while emission rates above 1000 t/d have been measured several times at San Cristóbal. Thus, episodes of strong magma degassing occur repeatedly at both volcanoes.

The plumes of San Cristóbal and Masaya seriously affect areas >20 km downwind, with atmospheric $SO_2$ concentrations that compare to, or exceed, those reported from large cities and areas downwind of industrial point sources. The low-altitude gas plume at Masaya has destroyed crops and other vegetation over several hundred km$^2$, and probably affects the health of thousands of people (Delmelle et al., 2002). San Cristóbal’s plume affects the entire area between the volcano and the city of Chinandega, 20 km away. The gas plume normally passes at the height of the crater rim, but under certain meteorological conditions, the gas flows down the volcano flank, and very high $SO_2$ concentrations are periodically observed in populated areas (data from Instituto Nicaragüense de Estudios Territoriales [INETER], www.ineter.gob.ni/). In the past 10 yr, Nicaraguan authorities repeatedly evacuated people from villages near San Cristóbal to prevent

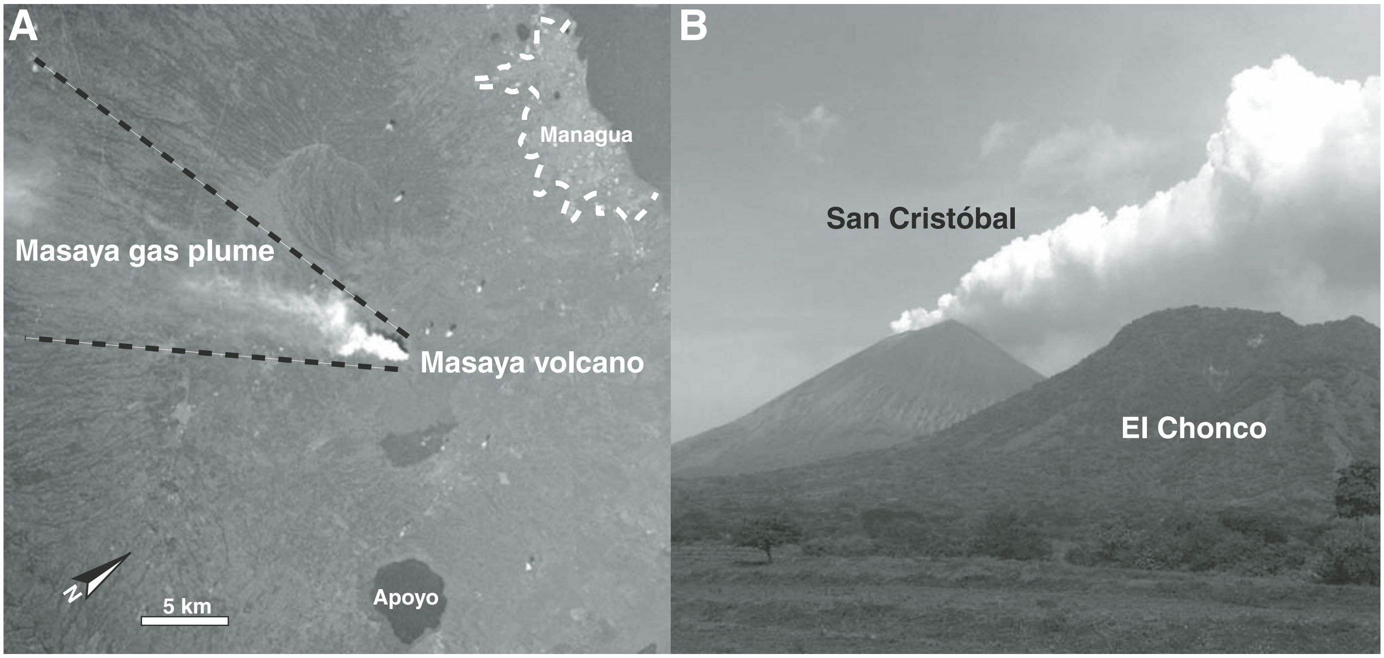

Figure 11. (A) Satellite image of the gas plume (between dashed lines) drifting from Masaya volcano. Satellite image from www.volcano.si.edu. (B) Gas plume emanating from San Cristóbal's crater.

injuries due to high gas concentrations. The U.S. National Air Quality Standard over the year is 30 ppbv of $SO_2$ (data from U.S. Environmental Protection Agency [EPA], www.epa.gov/oar/airtrends/sulfur2.html). Concentrations above this threshold value occur within several hundred $km^2$ at Masaya, San Cristóbal, and Telica volcanoes (Delmelle et al., 2002, 2001). Short-term (hours to days) concentration peaks can be much higher than long-term averages, thereby increasing the hazard.

Volcanic gases, particularly $CO_2$, emitted into deep crater lakes dissolve in the water until saturation is reached, which causes overturn of the water body and massive release of $CO_2$ clouds that flow along the ground. Such an invisible $CO_2$-cloud from Lake Nyos (Cameroon) killed 1700 people by asphyxiation in 1985 and raised the awareness that crater lakes need to be monitored at volcanoes with significant $CO_2$ degassing (Rice, 2000). Although no data is presently available on $CO_2$ degassing into Nicaraguan lakes, $CO_2$ degassing does occur along the volcanic arc (e.g., Lewicki et al., 2003). Deep lakes, such as Laguna de Apoyo (200 m) or Laguna Asososca near Managua (95 m), would be capable of generating large reservoirs of $CO_2$-saturated deep water.

## HAZARDS FROM MASS FLOWS AT VOLCANOES

### Lahars

Debris or mud flows that form at or near volcanoes are called lahars (Vallance, 2000) and are among the most dangerous volcanic phenomena, accounting for 10% of all volcanic fatalities (Schmincke, 2004). Lahars can originate by partial edifice collapse, by a variety of other mechanisms destabilizing sediment masses such as earthquakes or volcanic explosions, or by breaching and overspilling of a crater lake or melting of snow and ice by volcanic heat (Scott et al., 2005). Heavy rainfall onto loose ash is a particularly frequent cause of lahar formation (Hodgson and Manville, 1999; Lavigne and Thouret, 2003; Scott et al., 2005). Hence, they occur both related and unrelated to volcanic activity. Lahars are highly mobile and destructive flows that often reach tens of kilometers from a volcano, particularly when they ingest more sediment and water during runout. Mothes et al. (1998) reported a lahar deposit of almost 4 $km^3$ volume, reaching 326 km from Cotopaxi volcano in Ecuador.

The physical nature of lahars ranges from highly concentrated, coarse-grained debris flows of considerable strength through hyperconcentrated flows of intermediate sediment concentration (20–60 vol%) and viscosity to more dilute floods of muddy water (Pierson and Costa, 1987). The character and flow behavior of lahars typically change during runout. They may begin as concentrated mass flows that progressively dilute by loss of sediment or by mixing with stream water, or they may start as watery floods that may entrain up to four times their own volume in sediment (Cronin et al., 1997, 1999). Such bulking of lahars is facilitated where vegetation is absent or has been removed over large areas. Lahars flow through valleys but may spill over shallow channels and become wide on the flat plains around stratovolcanoes (Scott et al., 2005).

Lahars triggered by rainfall occurred repeatedly in Nicaragua during recent years (Scott et al., 2005). On 27 September

1996, a lahar from Maderas volcano destroyed houses in the village of El Corozal (600 inhabitants) and killed six people. Lahars descend yearly from Concepción volcano in the rainy season and reach up to 5 km away. Strong lahars occurred during Hurricane Mitch in 1998. Fresh ash erupted from San Cristóbal volcano from November 1999 on was remobilized as lahars with the beginning of the rainy season in May 2000 and flowed up to 15 km from the volcano.

Geologic mapping of historic and prehistoric deposits is essential to identifying lahar pathways, although numerical tools are available that analyze digitized topography for possible lahar channels (e.g., Iverson et al., 1998). Such models, however, do not yet fully capture the effects of bulking and de-bulking or the amount of sediment that can be mobilized, and predictions of strength and runout of lahars thus remain speculative.

Before the disaster of Hurricane Mitch, the hazard of landslides and lahars in Nicaragua was largely unknown, ignored, or underestimated, both by the general population and the scientific community. After 1998, an intense process started that embraced many projects carried out by foreign and national technical institutions and development aid agencies, improving the technical capacity at INETER, training local geoscientists in techniques for landslide identification and mapping, carrying out field investigations and air photo mapping of landslide occurrence, building up knowledge databases and geographic information systems (GIS) on these phenomena. In the last years, the INETER geophysical department has created a large GIS-based landslide inventory that contains georeferenced data of ~17,000 separate landslide events known in Nicaragua, including lahars and debris flows at the volcanoes. Landslide susceptibility and hazard maps were elaborated. Both conventional and interactive maps are accessible at INETER's Web site, www.ineter.gob.ni/geofisica/desliza/desliza.html. INETER worked also on the early warning system for possible lahars and landslides. A pilot project was carried out on the installation of telemetric meteorological stations at the volcanoes San Cristóbal, Casita, Mombacho, and Concepción to obtain data on the level of intensity and duration of intense precipitations that trigger lahars. Meteorological alerts in case of hurricanes or tropical depressions now always contain more detailed information about possible landslide occurrence. Also, public awareness of landslide and lahar hazards is much higher than before Hurricane Mitch. Local authorities report occurrences of lahars and landslides to INETER and request technical support for risk estimation and proposals for mitigation measures. The Nicaraguan Emergency Commission and Civil Defense actively support this process.

## Sector Collapse and Debris Avalanches

Processes leading to loss of structural integrity of volcanic edifices are various and occur on a range of timescales, from short-lived eruptive activity to gravitational settling over millennia (Borgia et al., 2000). Acidic waters reduce the competence of rocks that disintegrate to clay in the hydrothermal system inside a large volcano. Elevated pore pressures make volcanic edifices susceptible to failures. Edifices constructed with slopes at the angle of repose of volcaniclastic materials, or even with gentler slopes, that are internally weakened can suddenly collapse in response to some trigger (Cecchi et al., 2005). Such triggers include the inflation of the edifice by new magma, regional or volcanotectonic earthquakes, or massive intrusion of water during heavy rainfalls such as at Casita volcano in 1998. Most large volcanic edifices experience one or more sudden collapses, producing highly mobile gravity-controlled debris avalanches. These accelerate downhill and can flow at up to 100 km/h to distances of tens of kilometers. Debris avalanches destroy everything in their path and can leave breccia deposits thicker than 10 m. All stratocones in Nicaragua that possess active hydrothermal systems, and particularly those also affected by tectonic faults, can potentially experience flank collapse in the future. Below, we briefly summarize two collapse events that have occurred in the recent and historic past.

On 30 October 1998, a disastrous avalanche and lahar occurred after partial collapse of the southern summit of Casita (Sheridan et al., 1999), an older stratocone with flanks deeply incised by erosion. The collapse volume has been determined to be 1,600,000 m$^3$ (Kerle, 2002). The collapse was triggered by the exceptionally high precipitation (reaching a peak value of 59 mm/h prior to collapse; Scott et al., 2005) from Hurricane Mitch, which occurred late in the rainy season when the ground was already soaked with water. This trigger could operate because the Casita edifice was already structurally weakened by strong hydrothermal and meteoric alteration and fracturing of the rocks (Vallance et al., 2001a) with a high capacity for water infiltration and buildup of pore pressure (Kerle et al., 2003; Scott et al., 2005). Van Wyk de Vries et al. (2000) and Kerle et al. (2003) argue that the edifice was weakened by gravitational spreading and that the principal rupture of the collapse occurred along an ~400-m-long segment of a NE-trending fault intersecting the summit of Casita in an area of fumarolic and hydrothermal activity. Kerle et al. (2003) demonstrate that slow deformation had been going on at least since 1954 before the 1998 collapse and that there is geologic evidence of earlier landslide events, and van Wyk de Vries et al. (2000) argue that the tectonic, morphological, and hydrothermal state of Casita favors continuing deformation and the likelihood of another future collapse event.

The collapsing portion of the flank consisted of fractured andesitic lava and clay formed from hydrothermally altered scoria and was soaked with water. The avalanche descended the flank of the volcano through a deep erosional gully (Fig. 12), where it eroded sediment down to the bedrock. When spreading onto the plain at the base of Casita, the rock avalanche had transformed to a watery debris flow and a separate, highly concentrated flow that did not extend far onto the plain (Scott et al., 2005). The volume of the debris flow increased by entrainment of loose sediment as it surged across the plain, facilitated by deforestation (Kerle et

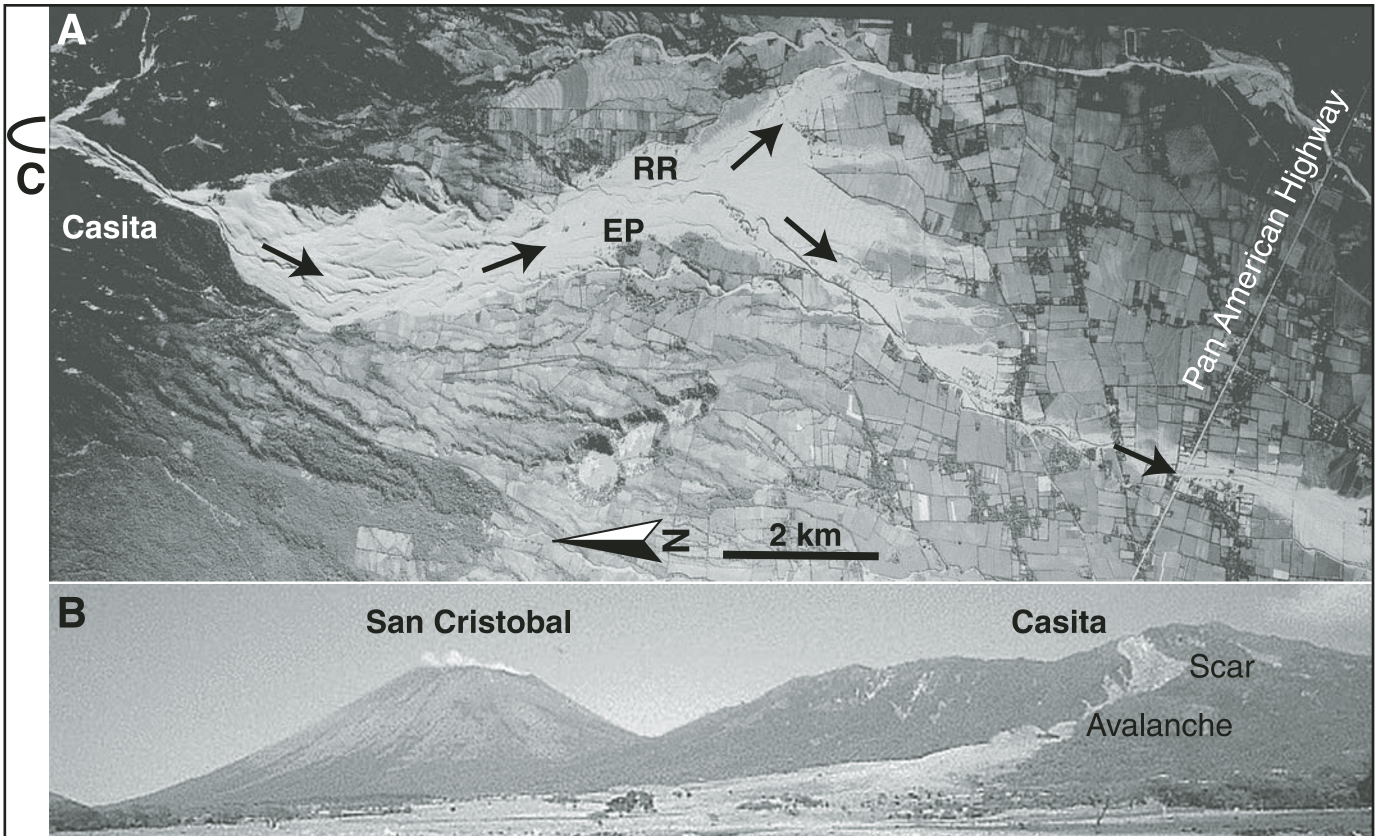

Figure 12. (A) Aerial photograph (from the U.S. Geological Survey) of the debris avalanche and lahar deposits spread from Casita volcano at left into cultivated and inhabited areas at right. C at left indicates source of collapse just outside picture. The avalanche descended through the narrow gorge on the flank, and the lahar spread widely onto the plain (arrows indicate flow directions). El Porvenir (EP) and Rolando Rodriguez (RR) were communities overrun by the lahar. (B) Surface of lahar deposits extending from the light-colored avalanche on the flank of Casita volcano in the background. Photograph from Instituto Nicaragüense de Estudios Territoriales, Managua.

al., 2003). When the lahar reached the villages of El Porvenir and Rolando Rodriguez, ~6 km from the collapse site (Fig. 12), only ~3 min after the collapse started (indicating an average speed of 120 km/h), it was 3–6 m deep, 1 km wide, and had bulked to ~4 times the initial volume (Scott et al., 2001, 2005). The two villages, which had been built only 15 yr before the disaster on deposits of prehistoric lahars, were completely destroyed, and more than 2000 people perished.

Similar to Casita, deeply dissected Mombacho volcano has a hydrothermally altered core. In 1570, an avalanche and debris flow on the south side of the volcano obliterated a town named Mombacho and killed more than 400 people. Historical accounts indicate that the collapse was preceded by earthquakes and accompanied by heavy rainfall, both potential triggers (Vallance et al., 2001b). Geologic evidence reveals three older, much larger, debris avalanches at the volcano that extend ~10 km from the summit to the southeast, northeast, and south and cover areas of 20–30 km$^2$. Two of these avalanches left thick, hummocky deposits that form a peninsula with a group of small islands, Las Isletas, along the shore of Lake Nicaragua (Vallance et al., 2001b). Entrance into the lake by these avalanches is likely to have triggered tsunamis.

## FROM HAZARD TO RISK

Volcanic risk is the product of volcanic hazard and vulnerability. Volcanic hazards are commonly described as the physical processes generating them and the areas that are potentially affected. Ideally, the hazards should be quantified in terms of the probability that they occur within a certain time and affect a given area, based on the past records of volcanoes, in order to facilitate long-term planning. This has been done, for example, for the Cerro Negro eruptions by Hill et al. (1998). For most other Nicaraguan volcanoes, however, extensive volcanological studies are still needed before such probabilistic quantifications can be made. Warning of an impending eruption on a shorter time scale (typically weeks to months) is achieved by a variety of techniques for monitoring unrest at volcanoes.

Vulnerability includes the threat to life and health and the degree of destruction of buildings, lifelines, industry, agriculture, and other economic activities by any kind of volcanic hazard. Vulnerability can be reduced by preparedness, which includes monitoring, mitigation, and emergency planning based on hazard maps and risk scenarios and public awareness and education.

## Forecast and Prediction

The ability to predict eruptions is especially important in densely populated areas to enable timely evacuation. Forecasts of volcanic activity are usually based on the past record of activity of a volcano and, therefore, are a relatively imprecise statement that can only be reasonably quantified if the volcano evolved in a fairly systematic fashion (cf. Fig. 7). However, apart from such empirical assessment, forecasting becomes increasingly supported by an improved understanding and modeling of the nonlinear dynamics that control the evolution of volcanoes (Sparks, 2003). Prediction is a relatively precise statement of the place, time, and ideally the nature of an impending eruption (Swanson et al., 1985) that is best derived from a combination of different monitoring techniques for detecting pre-eruptive unrest, as discussed in the next section.

Forecasts are hampered by periods of quiescence between eruptions varying greatly among, but also within, volcanoes. Generally, the longer a volcano has been dormant, the larger and more explosive a new eruption is (Simkin, 1993; Blong, 1996). Frequently active volcanoes such as Cerro Negro (22 eruptions since 1850), Masaya (23 since 1524), and Concepción (25 since 1800) have average quiescent periods on the order of 10 yr and produce eruptions with a volcanic explosivity index (VEI; Newhall and Self, 1982) of 0–3 on a logarithmic scale from 0 to 8 (data from Smithsonian Global Volcanism Program, www.volcano.si.edu). Cosigüina had seven eruptions since 1500, an average repose time near 100 yr, and eruptions ranged at VEI = 2–5. Eruptions from Chiltepe volcano, separated by periods on the order of $10^3$ years, had VEI = 4–5, and Apoyo caldera had two cataclysmic eruptions (VEI = 5–6) after an estimated quiescence on the order of $10^4$ years. Hence, the most hazardous volcanoes are commonly those for which eruptive phases are separated by hundreds or thousands of years of quiescence. There are no precise or generally accepted definitions for the terms *active volcano*, *dormant volcano*, and *extinct volcano*, but volcanoes that have erupted within the past 10,000 yr are commonly regarded as active by volcanologists (Simkin and Siebert, 2000), emphasizing the need for analysis of the deposits to arrive at reasonable estimations of the probability of future eruptions.

Volcanic eruptions typically comprise several episodes interrupted by quiescent periods. Total durations range from less than a day to tens of years; the median duration is ~50 days (Simkin and Siebert, 2000). Almost half the recorded eruptions reached their paroxysmal phase on the first day (Simkin and Siebert, 2000), followed by a slowly declining late phase. Obviously, emergency plans need to be ready in order to initiate countermeasures during the relatively short warning time prior to eruption provided by volcano monitoring.

## Monitoring

Monitoring is the continuous or frequently repeated measurement of geophysical, geological, and geochemical data that reflect processes operating at volcanoes. The four most important precursors to an impending eruption are (1) type, strength, and frequency of volcanic earthquakes; (2) varying magmatic pressure leading to surface deformation; (3) changes in volcanic gas flux and composition; and (4) increased heat flux. Other, less clear signs of unrest include changes in the electrical, magnetic, and gravity fields at a volcano. Most important is the analysis of seismic events and deformation of the surface that in many cases may allow short-term prediction of eruption site, onset (days to hours), but also of the type of eruption. Apart from eruption forecasting and hazard assessment, monitoring also provides essential data for understanding volcanic processes. With all monitoring techniques, possible precursors for an imminent volcanic eruption can only be estimated realistically when background behavior is known. In other words, a volcano must be observed over some time to recognize significant deviations from its "normal state."

### *Volcanic Earthquakes and Magma Ascent*

Volcanic earthquakes can be defined as seismic events generated in, below, and close to a volcano, as well as prior to, during, and after eruptions. Earthquakes from sudden stress release generate short seismic pulses, whereas magmatic and hydrothermal flow processes and related phenomena generate seismic waves that last from minutes to days, the so-called tremor. Permanent tremor recorded at Masaya volcano in 1992–1993, for example, originated from continuous degassing of magma residing in the conduit of Santiago crater (Métaxian et al., 1997).

All presently active volcanoes in Nicaragua (Cerro Negro, Concepción, Masaya, Momotombo, San Cristóbal, and Telica) are seismically monitored by INETER. At each of these volcanoes, a set of several short-period and two broad-band stations are installed. Also, all other important volcanic centers are monitored by at least one seismic short-period station. The data processing software employed by INETER's geophysical department (www.ineter.gob.ni/geofisica/geofisica.html) facilitates real-time analysis of the recordings. Earthquakes are located and their magnitudes are determined in near real time 24 hours daily by a qualified technician working with a monitoring and early warning system. Thus, it is sometimes possible to observe how a volcano builds up to an imminent eruption.

Although each volcano behaves individually, some common features of earthquake activity observed at different volcanoes suggest a general model (McNutt, 1996, 2000b). An initial swarm of high-frequency (5–15 Hz) earthquakes, occurring over a significant period of time, reflects fracturing of country rock at depth in response to increasing magma pressure. As magma reaches shallower levels, magmatic degassing and heat-induced hydrothermal flow and boiling induce lower-frequency (1–5 Hz) earthquakes and volcanic tremor (McNutt, 2000a, 2000b). In about a quarter of the investigated cases, the eruption was actually preceded by a period of relative seismic quiescence, reflecting stress release possibly by pressure venting through open cracks or heated wall rocks responding in ductile rather than brittle fashion (McNutt, 1996). During eruption, explosion earthquakes and eruption tremor result from magma flow and fragmentation. Magma withdrawal to depth and stress relaxation can return seismicity to deep, high-frequency earthquakes.

Real-time seismic amplitude measurements (RSAM), as made by INETER at San Cristóbal, Telica, Cerro Negro, Momotombo, Masaya, and Concepción volcanoes (www.ineter.gob.ni/geofisica/datrsam/), determine the seismic energy released, which is a proxy of strain rate (Sparks, 2003) if the seismic events are of tectonic type. Application of laws of materials failure provides a physical framework to interpret such data to predict the time of failure (i.e., the onset of eruption; Voight and Cornelius, 1991). Detailed seismic behavior at each volcano depends on numerous factors, such as geometry of the plumbing system, flow rate and volatile content of magma, and distribution of groundwater (McNutt, 2000b). Also, rather than magma ascent determining volcanic earthquakes, regional tectonic stresses and their associated earthquakes can control magma ascent and trigger an eruption, such as the one at Cerro Negro in 1999 (La Femina et al., 2004). Elevated seismicity is commonly the first sign of volcanic unrest, beginning hours to weeks before an eruption, but in many cases it is not followed by an eruption (Sparks, 2003). In order to judge whether earthquakes herald a forthcoming eruption or not, it is important to monitor the background seismicity in a volcanic area for several years (McNutt, 2000b).

During the last decade, INETER gathered experience in the monitoring and early warning of volcanic eruptions. Though not claiming the capacity for making a real prediction of the hour, magnitude, and duration of an eruption, INETER in several cases emitted warning messages hours, days, or weeks before the beginning of an eruption (Lesage et al., 2006). This was the case on 4 August 1995 at Cerro Negro. At 10 p.m. local time, very strong seismic activity with magnitudes up to 5.0 (Richter scale) was detected near the volcano. INETER immediately informed Civil Defense and the public. Civil Defense officials from their office in the city of León traveled to the volcano and stayed there during the night. The seismic activity turned into a continuous tremor, and INETER published, in the morning of 5 August, a warning about a pending volcanic eruption. Twelve hours after the seismic activity started, the Civil Defense officials observed the opening of a long fissure on the southern part of the volcano, and lava fountaining started. This and other examples are reported at www.ineter.gob.ni/geofisica/vol/alerta-temprana.html.

### *Volcano Deformation and Subsurface Mass Movements*

Beginning with the pioneering work of Eaton and Murata (1960), measuring tilt on the surface of volcanoes is the premier method for detecting an accumulation of magma in the interior of a volcano. The vertical and lateral expansion of the surface of a volcano can be measured very precisely and in real time with modern geodetic instruments, both conventional and using the global positioning system (GPS) (Van der Laat, 1996; Murray et al., 2000). A dramatic and accelerating radial tilt (>2000 µrad) was observed over two months at Mount St. Helens prior to its 1982 eruption (Dzurisin et al., 1983), whereas a much smaller tilt (<20 µrad) over about three weeks preceded the Pu'u 'O'o eruptions in Hawaii (Tilling and Dvorak, 1993). Eruption typically induces deflation of the edifice. Measurable ground deformation can occur even before seismic unrest begins, but then there are also volcanoes that do not deform prior to eruption (Sparks, 2003). Ground deformation is a measure of strain rates, which can also be measured directly using strainmeters (commonly installed in boreholes). Strain analysis in terms of failure criteria can thus principally be applied analogous to seismic data to determine the time of failure and eruption. The precision of such prediction, however, suffers from the complex mechanical response of volcanic edifices to magmatic pressure (Sparks, 2003). Next to predicting eruption time, horizontal and vertical displacements and tilt vectors measured by geodetic networks across a volcano can be used to determine the volume, shape, depth, and pressure of a magmatic intrusion and their variation with time (Van der Laat, 1996). Moreover, deformation of volcanic edifices not related to magma intrusion but to gravity, hydrothermal alteration, or regional tectonics (e.g., at Casita volcano; Van Wyk de Vries et al., 2000) can be geodetically monitored to identify possible future collapse sites. INETER employs GPS-based surface monitoring at all active Nicaraguan volcanoes, but does not have the capacity for real-time measurements and data processing. So, even when unrest has been detected, such as during the present crisis at Concepción volcano on Ometepe island (since July 2005), GPS equipment has to be transported to the field to set up the GPS sites, get the data to the office, send that data to cooperating scientific groups abroad for analysis, and get back the results. This process needs several days or weeks and is not actually useful for short-time prediction or warning.

Subsurface changes in density due to magma movement or degassing at depth are detected by gravity measurements, a technique that is best employed in conjunction with geodetic measurements, since changes in surface elevation also change the local gravity field. The combination of both techniques, called microgravity monitoring, is best applied to volcanoes where intruding magma has a significant density contrast to the host rock or where large volumes of exsolved gas may accumulate (Rymer, 1996). Applications of microgravity surveys have been most successful at andesitic stratovolcanoes, particularly when combined with seismic monitoring (e.g., see Voight et al., 1998). Gravity and deformation measurements made at Masaya volcano identified that the degassing crisis beginning in 1993 was not related to intrusion of new magma at depth (heralding a new phase of eruption) but to convective exchange of degassed with gas-rich resident magma at shallow levels (Rymer et al., 1998).

### *Volcanic Gas Flux and Composition*

The efflux and/or composition of gases that are released from a volcano can change prior to an eruption. $SO_2$ emissions may increase months or years prior to an eruption when new gas-rich magma intrudes the volcano (Kazahaya et al., 2004). Volcanic gases are mixtures of components (e.g., $H_2O$, $CO_2$, $SO_2$, F, Cl) released from magma at different depths and rates. Due to differences in pressure-dependent solubilities in magmas between such volatile species, changes in their proportions may indicate magma movement at depth potentially leading to eruption. Alternatively, the role of groundwater in the shallow magma plumbing system can be monitored using $SO_2$/halogen ratios in the volcanic plume (Edmonds et al., 2001). At Masaya volcano, the $SO_2$/HCl ratios changed abruptly from 1.8 to 4.6 prior to a phreatic eruption in 2001 (Duffell et al., 2003). This change could have reflected hydrothermal scavenging of HCl. Increased magma-water interaction may have played a role in triggering the eruption, showing the importance of chemical monitoring of volcanic gases. Thus, coupled changes in emission style and rate and gas composition are expected, and are highly relevant for monitoring purposes. Electrical self-potential measurements have been tested at Masaya volcano as a promising tool for investigating interactions between magmatic and groundwater systems (Lewicki et al., 2003). Routine sampling and analysis of fumarolic gases from assumed dormant volcanoes is also considered important, because reawakening of volcanoes should be visible through changes in the gas chemistry (e.g., Garofalo et al., 2006).

$SO_2$/HCl ratios can be measured using infrared spectroscopy (Fourier Transformation Infra-Red [FTIR] spectroscopy; e.g., Andres and Rose, 1995) or by direct analysis of fumarolic gases (Giggenbach, 1996). Due to the high solubility in water of both HCl and HBr, $SO_2$/BrO ratios in the plume measured by the mini-differential optical absorption–UV spectrometer (Galle et al., 2003) may similarly be used for monitoring the state of a volcano, though more needs to be understood concerning the chemistry of bromine in volcanic plumes (Bobrowski et al., 2003). Continuous ground-based remote sensing of $SO_2$ and BrO fluxes in volcanic plumes using the Mini-DOAS is a very promising tool for the chemical monitoring of permanently degassing volcanoes.

Through the past two decades, measurements of gas composition and fluxes have been made at Nicaraguan volcanoes (Mombacho, Masaya, Momotombo, Cerro Negro, Telica, San Cristóbal). INETER, in cooperation with the Instituto de Nacional de Sismología, Vulcanología, Meteorología, e Hidrología de Guatemala (INSIVUMEH), uses a correlation spectrometer to measure sulfur dioxide fluxes during volcanic crises. This was employed in August 2005 at the erupting Concepción volcano, where an emission of 400 t/d of $SO_2$ was recorded. Nevertheless, such measurements are limited to periods of only a few days per year and thus cannot be considered to reflect the real behavior of the gas emission of the volcanoes both in quantity and chemical composition. Therefore, application of the above mentioned Mini-DOAS technique to San Cristóbal and Masaya volcanoes is planned to begin in 2006 as part of a European Union program. The plan is to carry out a continuous automatic sampling during the day and to correlate the measurements with seismic and other continuous data streams.

### *Satellite Remote Sensing*

The rapid development in remote sensing by satellites during the past two decades has greatly increased the potential for monitoring volcanoes in the entire electromagnetic spectrum (Francis et al., 1996). Remote sensing is simply detection and measurement of electromagnetic radiation emitted from the surface of a volcano or from the atmosphere above. The radiation can be reflected sunlight, suitable for measuring changes in $SO_2$ emission (e.g., Krueger et al., 2000); infrared radiation, indicating changes in surface heat flux (e.g., Flynn et al., 2002); or the reflected pulse from a synthetic aperture radar (SAR) system that bombards a volcano with microwave energy and allows measurement of changes in ground elevation. Observations in the visible part of the electromagnetic spectrum are limited by cloud cover and daylight. Radar penetrates any type of weather but is insensitive to temperature. Modern satellites, therefore, carry multispectral sensors (Francis et al., 1996). Temporal resolution of satellite remote sensing is determined by their orbital path and revolution. Polar-orbiting satellites used for environmental monitoring (e.g., LANDSAT–thematic mapping instrument, National Oceanic and Atmospheric Administration–advanced very high resolution radiometer) revolve in ~90 min, but, since Earth rotates underneath them, the repeat cycle for a given area is ~12 h.

An advantage of space-borne surveillance is total areal coverage of a volcano. This is particularly interesting for surface deformation measurements using radar interferometry (Francis et al., 1996). This technique uses radar images from successive overflights in conjunction with topographic data to construct an interferogram that shows the temporal changes in distance between satellite and surface spots with a high vertical and lateral resolution. The high precision and dense areal coverage make SAR interferometry an interesting alternative to ground-based deformation measurements.

Measuring temperature is a standard monitoring technique that is applied by INETER during monthly visits to active volcanoes. Direct measurements of temperature in fumaroles, springs, and soil are complemented by satellite-based infrared sensors that can detect a 1000 °C hot spot of only 0.1 $m^2$ area, or detect temperature changes of a few tenths of a degree. Such thermal mapping has mostly been used to monitor ongoing eruptions. It proved useful, for example, in combination with seismic measurements to monitor the evolution of the 1997–2000 Colima eruption in México (Galindo and Dominguez, 2002). Weak ground heating as a possible precursor of eruption, however, is difficult to distinguish from other (mostly meteorological) effects (Francis et al., 1996). Twenty-three active volcanoes in Nicaragua and the whole of Central America are thermally monitored by INETER in real time using satellite images (AVHRR; e.g., Flynn et al., 2000, 2002). Thermal anomalies in the large open-vent volcanoes Telica and San Cristóbal can be detected by satellite (http://sat-server.ineter.gob.ni/page03/countries.htm).

Another important application of space-borne sensors is to monitor the height, topography, and aerosol content of spreading volcanic plumes (e.g., Carn et al., 2003). Moreover, satellite images are a valuable tool to help create hazard maps. After a disaster has struck, satellite images can provide an overview of the situation to adjust management strategies (Francis et al., 1996).

## Risk Assessment

Volcanic eruptions cannot be influenced by man now or in the foreseeable future. The risk, however, can be reduced by preparedness, which includes both plans for immediate crisis response as well as long-term plans to rearrange infrastructure in a way that reduces risk. The first step is risk identification by recognizing the volcanic hazards that may affect a given area and the factors that determine the vulnerability of that area (Blong, 2000). A convenient way to document the areal distribution of volcanic hazards is through hazard maps. Such maps outline areas that may be affected by volcanic phenomena, such as fallout, pyroclastic flows, or lahars, with a certain probability, typically distinguishing low, medium, and high risk zones. Hazard maps are traditionally based on volcanological studies of the eruptive history of a volcano. Each volcano behaves differently, requiring careful analysis of the local factors. In addition, advanced numerical models are increasingly used to define hazardous areas (Sparks, 2003). Tephra fallout dispersal can be modeled for given eruption conditions considering the local meteorological conditions (Carey, 1996; Rosi, 1998; Bonadonna et al., 2005). Other models, such as LAHARZ (Schilling, 1998) or TITAN-2D (Pitman et al., 2003), determine the spreading of various types of volcanic flows over digitized terrain. The risk for each area is then determined by the vulnerability derived from all information on infrastructure, such as population, buildings, lifelines, and industrial and agricultural use (Blong, 2000). Volcanic hazard and risk maps for Nicaraguan volcanoes were constructed by INETER (Delgado et al., 2002a, 2002b). Other hazard mapping projects are recently on the way for the volcanoes Telica, Cerro Negro, and El Hoyo. Figure 13 shows risk maps for some volcanic hazards at Concepción volcano, which was erupting (beginning 28 July 2005) at the time of this writing.

A useful tool in risk analysis is risk scenarios (Blong, 1996). These assume an eruption of a certain magnitude and intensity and evaluate its impacts on the various sectors of society. Such scenarios serve to develop crisis management plans but also to detect flaws in such plans. Another purpose is to define aims and priorities of long-term development planning both in urban and rural areas to reduce vulnerability (Blong, 1996). Hazard maps must be available and consulted by developers in order to avoid mistakes, such as the construction of the towns of El Porvenir and Rolando Rodriguez on the young lahar deposits at Casita volcano.

A critical question in creating risk scenarios is what kind of probable maximum eruption to use for a volcano (Blong, 1996). In the case of Cerro Negro, for example, the 1992 eruption is probably a reasonable choice of a maximum event (Hill et al., 1998). Masaya volcano has only produced small and mostly effusive eruptions largely limited to the caldera basin during the past <2000 yr (Walker et al., 1993), but large-magnitude eruptions as in earlier times (Pérez and Freundt, this volume) could occur again. Hence, it seems reasonable to create a set of risk scenarios considering a range of eruption types and magnitudes.

When creating risk scenarios or communicating with nonvolcanologists, it is useful to quantify hazards in terms of probability. Probabilities can be estimated with the help of probability trees. A simple example, based on the six youngest eruptions from the Chiltepe volcanic complex, is shown in Figure 14. In column 1, $P$ is the probability that an eruption will occur within a given time frame, which is not given a value here because of the uncertainties discussed in the context of Figure 7. Column 2 is the height of the eruption column, showing that 50% of the eruptions reached $H > 21$ km. Column 3 evaluates the sectorial direction of fallout dispersal, which depends on the column height and the present-day wind conditions as shown in Figure 4. For example, intermediate-height (14–21 km) columns have a 75% chance of being driven to the west. Column 4 is the thickness of fallout at a downwind distance of 15 km, where all (100%) past eruptions of $H > 21$ km produced deposits >1 m thick. Application to the town of Mateare indicates a 50% probability that $H > 21$ km, in which case, there is a 100% probability that the tephra thickness is >1 m. Hence, the probability that Mateare would get covered by >1 m tephra by the next eruption at Chiltepe is 0.5 × 1, or 50%. The probability that this will occur within a given time span would be $P \times 50\%$ (if, say, $P = 20\%$, then total probability is 10%). Column 4 may be replaced by column 5, which gives the thickness at 15 km distance in the cross-wind direction. For a westward dispersing eruption, this would apply to Managua. Again, there is a 50% probability that the eruption column would be higher than 21 km where the dispersal is always to the west. Since 66% of such eruptions deposited tephra thicker than 1 m in western Managua, the probability is 0.5 × 1 × 0.66, or 33%, that western Managua would be covered by such thickness during the next Chiltepe eruption. The factors considered in such probability trees depend on the kind of hazard studied. An analogous scheme could, for example, be designed to estimate the probability that a given area would be affected by pyroclastic surges. The reliability of the estimated probabilities, of course, increases with the number of past eruptions that have been recorded. The probability tree for fallout in León from Cerro Negro constructed by Connor et al. (2001) is based on 24 past events.

## Reducing Vulnerability

Preparedness of official authorities and individual people to manage an actual volcanic crisis through its advance, occurrence, and aftermath is an essential element in reducing vulnerability. Apart from the technical aspects discussed above, this includes efficient transfer of information between all parties involved and in particular, timely and appropriate information to the public, in a form that is understandable to nonspecialists (Johnston and Ronan, 2000). INETER publishes the actual conditions at the Nicaraguan volcanoes on its Web page (www.ineter.gob.

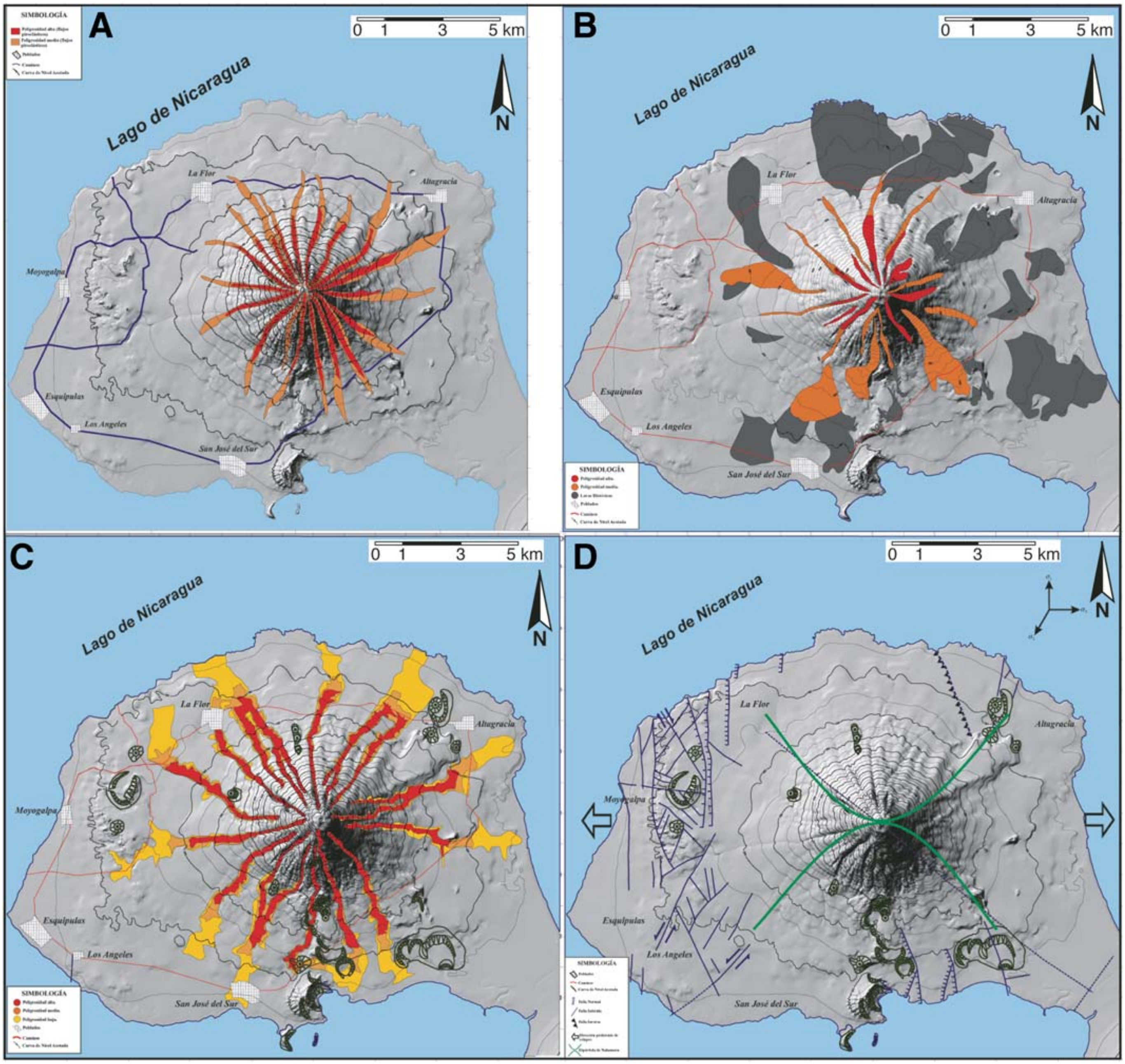

Figure 13. Maps of volcanic hazards and risk at Concepción volcano (Ometepe island, Lake Nicaragua) constructed by the Instituto Nicaragüense de Estudios Territoriales. (A) Pyroclastic-flow hazard zones. Red—high; orange—medium risk. (B) Lava-flow hazard zones. Red—high; orange—medium risk; dark gray—historic lava flows. (C) Lahar hazard zones. Red—high; orange—medium; yellow—low risk. (D) Probable direction of flank collapse to either east or west (arrows) determined from tectonic structures (blue—faults). Flow paths in (A) and (C) were determined by the Flow3D numerical model (see Delgado et al., 2002a).

ni/geofisica/vol/dep-vol.html) and in monthly bulletins (www.ineter.gob.ni/geofisica/sis/bolsis/bolsis.html). Receptivity of the public to information is best when awareness of volcanic hazards has been created by public education. Education programs have been set up in many volcanic areas around the world (Johnston and Ronan, 2000), including community disaster training. The International Association of Volcanology and Geochemistry of the Earth's Interior (IAVCEI; www.iavcei.org) produced video tapes, "Understanding volcanic hazards" and "Reducing volcanic risk," that may be used in such programs. One step in this direction in Nicaragua, for example, is the book *Amenazas Naturales de Nicaragua (Natural Hazards in Nicaragua)*, published and distributed by INETER (www.ineter.gob.ni/geofisica/amenazas/libro-amenazas.html).

In the long run, adjusting rural and urban development to avoid high-risk areas is probably the most efficient way to reduce vulnerability. For one, when a new settlement is planned somewhere, the ground must be checked for previous hazardous volcanic events. Secondly, based on hazard and risk maps, areas of high risk must be delineated far in advance in order to avoid the pressure of individuals, communities, or commercial interest to open up new land for developments. In the last few years, several projects have been carried out in Nicaragua to achieve these goals. A World Bank–financed project directed by the Nicaraguan Emergency Commission (SINAPRED) and technically supervised by INETER combined hazard and vulnerability maps with proposals for land use planning in 30 high-risk municipalities in the country, most of them located in or near the volcanic chain. Since 2004, INETER, by request of the National House Construction Authority (INVUR) and local authorities, elaborated hazard studies at 90 sites all over the country (www.ineter.gob.ni/geofisica/proyectos/INVUR/index.html), some of them in rural areas that are affected by volcanic hazards. For these sites, the construction of new houses in high risk areas is avoided or only permitted with accompanying mitigation or prevention measures.

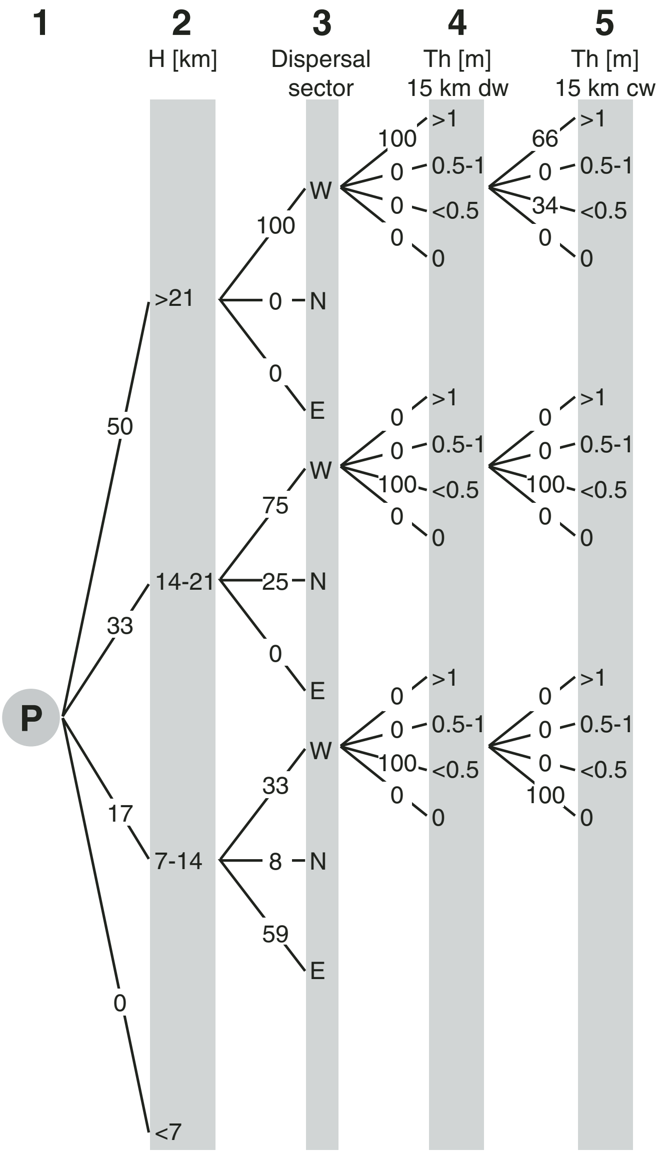

Figure 14. Probability tree for fallout tephra accumulation 15 km from vent by an eruption at Chiltepe peninsula. Only some of the branches are continued from column 1 through 4; column 5 (thickness at 15 km cross-wind-distance) may replace column 4 (thickness at 15 km downwind-distance). P in column 1 is the probability that an eruption will occur within a given time frame. Numbers on connecting lines give probabilities in percent based on past six eruptions since ~15,000 yr ago (columns 2, 4, 5) and on present-day wind conditions (column 3). See text for discussion.

In times of crisis, the efficiency of monitoring and early warning systems is certainly a crucial factor in reducing vulnerability. The instrumental base of the volcano monitoring and early warning system developed and maintained by INETER has dramatically improved over the last decade by international help, support from the Nicaraguan government, and engagement of the Nicaraguan scientists and technicians. During this period, no disastrous volcanic emergency has occurred in Nicaragua (the 1998 Mitch disaster had no direct volcanic cause). However, as discussed above, a dramatic volcanic emergency might arise, for example, at Apoyeque volcano, very close to the Managua-Masaya area, the largest Nicaraguan population center. The capacity of technical personnel is certainly decisive as to whether optimal use is made of the monitored data in case of an emergency. INETER's volcanology group is very small, but it is permanently assisted by seismology, applied geology, and GIS groups comprising INETER's geophysical department, which is the multidisciplinary body necessary to understand and manage the technical aspects of a volcanic crisis. General knowledge, academic level, and scientific capacity are steadily improving in the geophysical department. However, as in other institutions important for the handling of volcanic crises, many deficiencies remain and need to be coped with. Both progress and problems must be seen in the light of the fact that Nicaragua has only recently passed through a deep socioeconomic crisis and is slowly recovering but is still considered the second poorest country in the Americas. Thus, permanent relations with foreign expert groups such as the U.S. Geological Survey–Volcano Disaster Program (VDAP) and other aid institutions must be, and are considered by Nicaragua to be, essential in the case of a volcano emergency with its dramatic human, social, economic, and political implications.

## SUMMARY AND CONCLUSIONS

The flanks and foothills around the active volcanoes of Nicaragua are endangered in many different ways. Highly destructive flank collapses of volcanoes, producing huge debris avalanches and debris flows, are comparatively rare. Particularly hazard-prone areas are the valleys that radiate from volcano flanks, because they channelize high-velocity pyroclastic flows and watery debris flows (lahars), which carry destruction for many tens of kilometers into the foreland (rarely >100 km) and can be generated many years to decades after a volcanic eruption. Over the past 200 yr, most people worldwide were killed during volcanic eruptions by pyroclastic flows and surges, lahars, and volcanogenic tsunamis (Blong, 1996). Fallout of ash and coarser rock fragments cause the overloading and collapse of roofs, particularly relatively close downwind of a volcano. The hazards of fine ash clouds to air traffic have also become apparent in the past few decades from the more than a dozen near catastrophes, which occurred when large jets crossed ash clouds and their turbines became clogged. The entry of debris avalanches or large pyroclastic flows into Lake Managua or Lake Nicaragua, as well as explosive eruptions within or close to these lakes, can generate destructive and lethal tsunamis. The explosive interaction between rising magma and groundwater or surface water is especially dangerous. In many volcanic eruptions, several of these hazard phenomena can occur almost simultaneously. Toxic gases permanently emitted from open vents are a health hazard to people and animals and pollute water and soil downwind of active volcanoes.

The greatest volcanic fatalities in the twentieth century resulted from relatively small eruptions in areas with high population density. The catastrophic effect was due to their sudden onset, which prevented a timely evacuation, or to political reasons, which delayed response planning. Predicting the type of an eruption, its location, and if possible its onset requires very careful analysis of the development of the history of a volcano. Successful predictions require long-term monitoring to understand the characteristic behavior of volcanoes prior to large eruptions. The most important monitoring methods are to record magnitudes and rate changes of volcanic earthquakes, swelling of the volcanic edifice, and gas emissions, especially of $SO_2$. The rapid developments in remote sensing via satellites have significantly increased the possibility for monitoring volcanoes using the entire electromagnetic spectrum and providing complete areal coverage.

Volcanic catastrophes have developed when people did not protect themselves early enough in the face of an impending volcanic eruption. This problem is magnified by the pressure of growing populations who settle the fertile slopes of active volcanoes. This makes it increasingly difficult to prevent potentially hazardous areas from being occupied by people. Clearly, societies today are much more vulnerable vis-à-vis volcanic and other natural hazards than in the past, particularly through the rapid growth of megacities and the increasingly intricate networks of traffic, communication, and supply lines.

After the disaster of Hurricane Mitch in 1998, Nicaragua has significantly increased its technical and organizational capacity for disaster management, the extent and quality of databases on volcanic and other hazards, and the availability of hazard, vulnerability, and risk maps for scientific purposes and land use planning by local and central governmental administrations and the general public. Nicaragua's monitoring and early warning system on volcanic phenomena has developed greatly over the last few years. Real-time GPS measurements, continuous sampling of amount and composition of volcanic gas emissions, and densification of seismic networks around the active volcanoes and densely populated areas were important steps for the improvement of the system. Cooperation with international expert groups is essential for volcano hazard assessment and adequate management of volcanic crisis. Challenges for the future include the training of volcanologists to be able to correctly interpret the signals of the complex volcano monitoring system, the education of the population for adequate behavior when an eruption occurs, and the training of the planners and decision makers to optimize land use while taking into account volcano risks.

## APPENDIX: GLOSSARY OF MAJOR TECHNICAL TERMS

Definitions are from Schmincke, 2004.

**Volcanic hazard** to people and property is a threatening event that is defined by a particular type, magnitude, and probability of occurrence of volcanic activity. Volcanic hazards in Nicaragua take many forms, as discussed in this chapter.

**Vulnerability** is defined as the degree to which the entire community is subject to impacts of hazards. This includes lives, property, essential environmental resources, economy, and standards of living.

**Volcanic risk** is applied to volcanic hazard in relation to life or property in a particular spot and at a particular time. Risk is then a combination of hazard features (which are specific to each volcano) and local valuable elements (including population, resources and infrastructure). People, property and natural resources are vulnerable to hazards when situated too close to a volcano, or, more specifically, to potential processes within a particular form of eruption.

**Disasters** result from the interaction of natural events with political, economic, social, and technological processes. Disasters occur when people do not recognize the potential hazards of a volcano or particular types of volcanic eruptions, warnings from the volcano itself, or from scientists and hence do not protect themselves through mitigation and emergency response plans. In addition, political issues and insufficient communication between scientists, community leaders, and emergency managers often lead to the worst types of volcanic disaster. A volcanic disaster or catastrophe strikes when the scale or particular nature of a volcanic event exceeds the capacity of a community to cope. The ability to cope depends on the economic potential of a community or country and the strength of private or public institutions capable of quickly and effectively responding to a hazardous natural event.

**Disaster mitigation** includes all activities toward reducing risk, either the hazards (via physical interventions; e.g., sabo dams) or vulnerability (via hazard mapping, land use planning). It also includes preparation by responsible administrative bodies and civil protection authorities as well as a public that is fully informed about all possibilities, including evacuation measures. This is a formidable task, because the spectrum of volcanic eruptions in Nicaragua and, therefore, hazard types is large.

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## REFERENCES CITED

Andres, R.J., and Rose, W.I., 1995, Remote sensing spectroscopy of volcanic plumes and clouds, *in* McGuire, B., Kilburn, C., and Murray, J., eds., Monitoring Active Volcanoes: Strategies, Procedures and Techniques: London, UCL Press Limited, p. 301–314.

Andres, R.J., and Kasgnoc, A.D., 1998, A time-averaged inventory of subaerial volcanic sulfur emissions: Journal of Geophysical Research, v. 103, p. 25,251–25,261, doi: 10.1029/98JD02091.

Bacon, C.R., 1982, Time-predictable bimodal volcanism in the Coso Range, California: Geology, v. 10, p. 65–69, doi: 10.1130/0091-7613(1982)10<65:TBVITC>2.0.CO;2.

Baxter, P.J., 2000, Impacts of eruptions on human health, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: New York, Academic Press, p. 1035–1044.

Beget, J.E., 2000, Volcanic tsunamis, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: New York, Academic Press, p. 1005–1014.

Belousov, A., Voight, B., Belousova, M., and Muravyev, Y., 2000, Tsunamis generated by subaquatic volcanic explosions: Unique data from 1996 eruption in Karymskoye Lake, Kamchatka, Russia: Pure and Applied Geophysics, v. 157, p. 1135–1143, doi: 10.1007/s000240050021.

Bice, D.C., 1985, Quaternary volcanic stratigraphy of Managua, Nicaragua: Correlation and source assignment for multiple overlapping plinian deposits: Geological Society of America Bulletin, v. 96, p. 553–566, doi: 10.1130/0016-7606(1985)96<553:QVSOMN>2.0.CO;2.

Blong, R.J., 1996, Volcanic hazards risk assessment, *in* Scarpa, R., and Tilling, R.I., eds., Monitoring and mitigation of volcano hazards: Berlin, Springer, p. 675–698.

Blong, R., 2000, Volcanic hazards and risk management, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: New York, Academic Press, p. 1215–1227.

Bobrowski, N., Hönninger, G., Galle, B., and Platt, U., 2003, Detection of bromine monoxide in a volcanic plume: Nature, v. 423, p. 273–276, doi: 10.1038/nature01625.

Bonadonna, C., Phillips, J.C., and Houghton, B.F., 2005, Modeling tephra sedimentation from a Ruapehu weak plume eruption: Journal of Geophysical Research, v. 110, doi:10.1029/2004JB003515.

Borgia, A., Delaney, P.T., and Denlinger, R.P., 2000, Spreading volcanoes: Annual Review of Earth and Planetary Sciences, v. 28, p. 539–570, doi: 10.1146/annurev.earth.28.1.539.

Borgia, A., and van Wyk de Vries, B., 2003, The volcano-tectonic evolution of Concepción, Nicaragua: Bulletin of Volcanology, v. 65, p. 248–266.

Carey, S.N., 1996, Modeling of tephra fallout from explosive eruptions, *in* Scarpa, R., and Tilling, R.I., eds., Monitoring and mitigation of volcano hazards: Berlin, Springer, p. 429–461.

Carey, S., Morelli, D., Sigurdsson, H., and Bronto, S., 2001, Tsunami deposits from major explosive eruptions: An example from the 1883 eruption of Krakatau: Geology, v. 29, p. 347–350, doi: 10.1130/0091-7613(2001)029<0347:TDFMEE>2.0.CO;2.

Carn, S.A., Krueger, A.J., Bluth, G.J.S., Schaefer, S.J., Krotkov, N.A., Watson, I.M., and Datta, S., 2003, Volcanic eruption detection by the Total Ozone Mapping Spectrometer (TOMS) instruments: A 22-year record of sulphur dioxide and ash emissions, *in* Oppenheimer, C., Pyle, D.M., and Barclay, J., Volcanic degassing: London, Geological Society Special Publication 213, p. 177–202.

Carr, M.J., 1984, Symmetrical and segmented variation of physical and geochemical characteristics of the Central American volcanic front: Journal of Volcanology and Geothermal Research, v. 20, p. 231–252, doi: 10.1016/0377-0273(84)90041-6.

Carr, M.J., Rose, W.I., and Stoiber, R.E., 1982, Central America, *in* Thorpe, R.S., ed., Andesites: Orogenic Andesite and Related Rocks: New York, Wiley, p. 149–166.

Cecchi, E., van Wyk de Vries, B., and Lavest, J.-M., 2005, Flank spreading and collapse of weak-cored volcanoes: Bulletin of Volcanology, v. 67, p. 72–91.

Connor, C.B., Hill, B.E., Winfrey, B., Franklin, N.M., and LaFemina, P.C., 2001, Estimation of volcanic hazards from tephra fallout: Natural Hazards Review, v. 2, p. 33–42, doi: 10.1061/(ASCE)1527-6988(2001)2:1(33).

Cronin, S.J., Neall, V.E., Lecointre, J.A., and Palmer, A.S., 1997, Changes in Whangaehu River lahar characteristics during the 1995 eruption sequence, Ruapehu volcano, New Zealand: Journal of Volcanology and Geothermal Research, v. 76, p. 47–61, doi: 10.1016/S0377-0273(96)00064-9.

Cronin, S.J., Neall, V.E., Lecointre, J.A., and Palmer, A.S., 1999, Dynamic interactions between lahars and stream flow: A case study from Ruapehu volcano, New Zealand: Geological Society of America Bulletin, v. 111, p. 28–38, doi: 10.1130/0016-7606(1999)111<0028:DIBLAS>2.3.CO;2.

Delgado, H., Navarro, M., Abimelec, I., and Alatorre, M.A., 2002a, Volcanic hazards map of Concepción volcano: Universidad Nacional Autónoma de México and the Instituto Nicaragüense de Estudios Territoriales, Managua, maps and report, in Spanish, scale 1:50,000, 78 p.

Delgado, H., Navarro, M., Abimelec, I., and Horst, M.A., 2002b, Volcanic hazards map of Masaya volcano: Universidad Nacional Autónoma de México and the Instituto Nicaragüense de Estudios Territoriales, Managua, maps and report, in Spanish, scale 1:50,000, 120 p.

Delmelle, P., Stix, J., Baxter, P.J., Garcia-Alvarez, J., and Barquero, J., 2002, Atmospheric dispersion, environmental effects and potential health hazard associated with the low-altitude gas plume of Masaya volcano, Nicaragua: Bulletin of Volcanology v. 64, p. 423–434, doi: 10.1007/s00445-002-0221-6.

Delmelle, P., Stix, J., Bourque, C.P.A., Baxter, P.J., Garcia-Alvarez, G., and Barquero, J., 2001, Dry deposition and heavy acid loading in the vicinity of Masaya volcano, a major sulfur and chlorine source in Nicaragua: Environmental Science & Technology, v. 35, p. 1289–1293, doi: 10.5555/es000153m.

de Oviedo y Valdes, G.F., 1855, Historia General y Natural de las Indias, *in* Amador de los Rios, J., ed., Madrid, v. 3-4, p. 70–92.

Duffell, H.J., Oppenheimer, C., Pyle, D.M., Galle, B., McGonigle, A.J.S., and Burton, M.R., 2003, Changes in gas composition prior to a minor explosive eruption at Masaya volcano, Nicaragua: Journal of Volcanology and Geothermal Research, v. 126, p. 327–339, doi: 10.1016/S0377-0273(03)00156-2.

Dzurisin, D., Westphal, J.A., and Johnson, D.J., 1983, Eruption prediction aided by electronic tiltmeter data at Mount St. Helens: Science, v. 221, p. 1381–1383.

Eaton, J.P., and Murata, D.J., 1960, How volcanoes grow: Science, v. 132, p. 925–938.

Edmonds, M., Pyle, D., and Oppenheimer, C., 2001, A model for degassing at the Soufriere Hills Volcano, Montserrat, West Indies, based on geochemical data: Earth and Planetary Science Letters, v. 186, p. 159–173, doi: 10.1016/S0012-821X(01)00242-4.

Flynn, L.P., Harris, A.J.L., Rothery, D.A., and Oppenheimer, C., 2000, Landsat and hyperspectral analyses of active lava flows, *in* Mouginis-Mark, P.J., Fink, J.H., and Crisp J.A., eds., Remote sensing of active volcanism: American Geophysical Union Geophysical Monograph Series, v. 116, p. 161–177.

Flynn, L., Wright, R., Garbeil, H., Harris, A., and Pilger, E., 2002, A global thermal alert system using MODIS: Initial results from 2000–2001: Advances in Environmental Monitoring and Modelling, v. 1, p. 37–69.

Francis, P.W., and Oppenheimer, C., 2004, Volcanoes, 2nd edition: Oxford, Oxford University Press, 534 p.

Francis, P.W., Wadge, G., and Mouginis-Mark, P.J., 1996, Satellite monitoring of volcanoes, *in* Scarpa, R., and Tilling, R.I., eds., Monitoring and mitigation of volcano hazards: Berlin, Springer, p. 257–298.

Freundt, A., 2003, Entrance of hot pyroclastic flows into the sea: Experimental observations: Bulletin of Volcanology v. 65, p. 144–164.

Freundt, A., Wilson, C.J.N., and Carey, S.N., 2000, Ignimbrites and block-and-ash flows, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: New York, Academic Press, p. 581–599.

Freundt, A., Kutterolf, S., Wehrmann, H., Schmincke, H.U., and Strauch, W., 2006, Tsunami generated by a compositionally zoned plinian eruption at Chiltepe peninsula, Lake Managua (Xolotlan), Nicaragua: Journal of Volcanology and Geothermal Research, v. 149, p. 103 123, doi: 10.1016/j.jvolgeores.2005.06.001.

Gaceta Oficial de Nicaragua, 1886, Eruption of Momotombo: Managua, Gaceta Oficial de Nicaragua.

Galindo, I., and Dominguez, T., 2002, Near real-time satellite monitoring during the 1997–2000 activity of Volcan de Colima (Mexico) and its relationship with seismic monitoring: Journal of Volcanology and Geothermal Research, v. 117, p. 91–104, doi: 10.1016/S0377-0273(02)00238-X.

Galle, B., Oppenheimer, C., Geyer, A., McGonigle, A., Edmonds, M., and Horrocks, L., 2003, A miniaturised ultraviolet spectrometer for remote sensing of $SO_2$ fluxes: A new tool for volcano surveillance: Journal of Volcanology and Geothermal Research, v. 119, p. 241–254, doi: 10.1016/S0377-0273(02)00356-6.

Garofalo, K., Tassi, F., Vaselli, O., Delgado-Huertas, A., Tedesco, D., Frische, M., Hansteen, T.H., Poreda, R.J., and Strauch, W., 2006, The fumarolic gas discharges at Mombacho Volcano (Nicaragua): Presence of magmatic gas species and implications for a volcanic surveillance: Bulletin of Volcanology (in press).

Giggenbach, W.F., 1996, Chemical composition of volcanic gases, *in* Scarpa, M., and Tilling, R.J., eds., Monitoring and mitigation of volcanic hazards: Berlin, Springer-Verlag, p. 221–256.

Hazlett, R.W., 1987, Geology of the San Cristóbal volcanic complex, Nicaragua: Journal of Volcanology and Geothermal Research, v. 33, p. 223–230, doi: 10.1016/0377-0273(87)90064-3.

Hill, B.E., Connor, C.B., Jarzemba, M.S., and La Femina, P.C., 1998, 1995 eruptions of Cerro Negro, Nicaragua, and risk assessment for future eruptions: Geological Society of America Bulletin, v. 110, p. 1231–1241, doi: 10.1130/0016-7606(1998)110<1231:EOCNVN>2.3.CO;2.

Hodgson, K.A., and Manville, V.R., 1999, Sedimentology and flow behavior of a rain-triggered lahar, Mangatoetoenui Stream, Ruapehu volcano, New Zealand: Geological Society of America Bulletin, v. 111, p. 743–754, doi: 10.1130/0016-7606(1999)111<0743:SAFBOA>2.3.CO;2.

Hradecky, P., 2001, Informe final de consultoria para el proyecto "Actualización del mapa geológico-estructural del area de Managua": Managua, Instituto Nicaragüense de Estudios Territoriales.

Instituto Nicaragüense de Estudios Territoriales (INETER), 2005, Situación actual: www.ineter.gob.ni/geofisica/desliza/desliza.html (last accessed June 2006).

Iverson, R.M., Schilling, S.P., and Vallance, J.W., 1998, Objective delineation of lahar-inundation hazard zones: Geological Society of America Bulletin, v. 110, p. 972–984, doi: 10.1130/0016-7606(1998)110<0972:ODOLIH>2.3.CO;2.

Johnston, D., and Ronan, K., 2000, Risk education and intervention, *in* Sigurdsson, H., eds., et al., Encyclopedia of Volcanoes: New York, Academic Press, p. 1229–1240.

Kazahaya, K., Shinohara, H., Uto, K., Odai, M., Nakahori, Y., Mori, H., Iino, H., Miyashita, M., and Hirabayashi, J., 2004, Gigantic $SO_2$ emission from Miyakejima volcano, Japan, caused by caldera collapse: Geology, v. 32, p. 425–428, doi: 10.1130/G20399.1.

Kerle, N., 2002, Volume estimation of the 1998 flank collapse at Casita volcano, Nicaragua—a comparison of photogrammetric and conventional techniques: Earth Surface Processes and Landforms, v. 27, p. 759–772, doi: 10.1002/esp.351.

Kerle, N., van Wyk de Vries, B., and Oppenheimer, C., 2003, New insight into the factors leading to the 1998 flank collapse and lahar disaster at Casita volcano, Nicaragua: Bulletin of Volcanology, v. 65, p. 331–345.

Krueger, A.J., Schaefer, S.J., Krotkov, N., Bluth, G., and Barker, S., 2000, Ultraviolet remote sensing of volcanic emissions, *in* Mouginis-Mark, P.J., Crisp, J.A., and Fink, J.H., eds., Remote Sensing of Active Volcanism: American Geophysical Union, Geophysical Monograph Series, v. 116, p. 25–43.

Kutterolf, S., Schacht, U., Wehrmann, H., Freundt, A., and Mörz, T., 2006, Onshore to offshore tephrostratigraphy and marine ash layer diagenesis in Central America, *in* Bundschuh, J., and Alvarado, G.E., eds., Central America—Geology, Resources and Hazards: Rotterdam, Balkema (in press).

La Femina, P.C., Connor, C.B., Hill, B.E., Strauch, W., and Armando Saballos, J., 2004, Magma-tectonic interactions in Nicaragua: The 1999 seismic swarm and eruption of Cerro Negro volcano: Journal of Volcanology and Geothermal Research, v. 137, p. 187–199, doi: 10.1016/j.jvolgeores.2004.05.006.

Lavigne, F., and Thouret, J.C., 2003, Sediment transport and deposition by rain-triggered lahars at Merapi volcano, Central Java, Indonesia: Geomorphology, v. 49, p. 45–69, doi: 10.1016/S0169-555X(02)00160-5.

Lesage, Ph., Mora, M., Strauch, W., Escobar, D., Matías, O., Tenorio, V., Talavera, E., Rodríguez, A., and Alvarado, G., 2006, Volcano Seismology, *in* Bundschuh, J., and Alvarado, G.E., eds., Central America—Geology, Resources and Hazards: Rotterdam, Balkema (in press).

Lewicki, J.L., Connor, C., St-Amand, K., Stix, J., and Spinner, W., 2003, Self-potential, soil $CO_2$ flux, and temperature on Masaya volcano, Nicaragua: Geophysical Research Letters, v. 30, p. 1817, doi: 10.1029/2003GL017731.

McBirney, A.R., 1956, The Nicaraguan volcano Masaya and its caldera: Eos (Transactions, American Geophysical Union), v. 37, p. 83–96.

McBirney, A.R., and Williams, H., 1965, Volcanic history of Nicaragua: University of California Publications in Geological Science, v. 55, p. 1–65.

McKnight, S.B., and Williams, S.N., 1997, Old cinder cone or young composite volcano?: The nature of Cerro Negro, Nicaragua: Geology, v. 25, p. 339–342, doi: 10.1130/0091-7613(1997)025<0339:OCCOYC>2.3.CO;2.

McNutt, S.R., 1996, Seismic monitoring and eruption forecasting of volcanoes: A review of the state-of-the-art and case histories, *in* Scarpa, R., and Tilling, R.I., eds., Monitoring and mitigation of volcano hazards: Berlin, Springer, p. 99–146.

McNutt, S.R., 2000a, Volcanic seismicity, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: New York, Academic Press, p. 1015–1033.

McNutt, S.R., 2000b, Seismic monitoring, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: New York, Academic Press, p. 1095–1119.

Métaxian, J.P., Lesage, P., and Dorel, J., 1997, Permanent tremor of Masaya volcano, Nicaragua: Wave field analysis and source location: Journal of Geophysical Research, v. 102, p. 22,529–22,545, doi: 10.1029/97JB01141.

Miller, T.P., and Casadevall, T.J., 2000, Volcanic ash hazards to aviation, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: New York, Academic Press, p. 915–930.

Mothes, P.A., Hall, M.L., and Janda, R.J., 1998, The enormous Chillos Valley lahar: An ash-flow-generated debris flow from Cotopaxi volcano, Ecuador: Bulletin of Volcanology v. 59, p. 233–244, doi: 10.1007/s004450050188.

Murray, J.B., Rymer, H., and Locke, C.A., 2000, Ground deformation, gravity, and magnetics, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: New York, Academic Press, p. 1121–1140.

Newhall, C.G., and Self, S., 1982, The volcanic explosivity index (VEI): An estimate of explosive magnitude for historical volcanism: Journal of Geophysical Research, v. 87, p. 1231–1238.

Pérez, J., 1993, Obras Históricas Completas, 2nd edition: Managua, Fondo de Promoción Cultural, BANIC, p. 793

Pérez, W., and Freundt, A., this volume, The youngest highly explosive basaltic eruptions from Masaya Caldera (Nicaragua): Stratigraphy and hazard assessment, *in* Rose, W.I., Bluth, G.J.S., Carr, M.J., Ewert, J.W., Patino, L., and Vallance, J.W., Volcanic hazards in Central America: Geological Society of America Special Paper 412, doi: 10.1130/2006.2412(10).

Pierson, T.C., and Costa, J.E., 1987, A rheological classification of subaerial sediment-water flows, *in* Costa, J.E., and Wieczorek, G.F., eds., Debris flows/avalanches: Process, recognition and mitigation: Reviews in Engineering Geology, v. 7, p. 1–12.

Pitman, E.B., Nichita, C.C., Patra, A., Bauer, A., Sheridan, M., and Bursik, M., 2003, Computing granular avalanches and landslides: Physics of Fluids, v. 15, p. 3638–3646, doi: 10.1063/1.1614253.

Protti, M., Gundel, F., and McNally, K., 1995, Correlation between the age of the subducting Cocos plate and the geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica, *in* Mann, P., eds., Geologic and tectonic development of the Caribbean plate boundary in southern Central America: Geological Society of America Special Paper 295, p. 309–326.

Pyle, D.M., 2000, Sizes of volcanic eruptions, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: New York, Academic Press, p. 263–270.

Ranero, C.R., von Huene, R., Flueh, E., Duarte, M., Baca, D., and McIntosh, K., 2000, A cross section of the convergent Pacific margin of Nicaragua: Tectonics, v. 19, p. 335–357, doi: 10.1029/1999TC900045.

Rice, A., 2000, Rollover in volcanic crater lakes: A possible cause for Lake Nyos type disasters: Journal of Volcanology and Geothermal Research, v. 97, p. 233–239, doi: 10.1016/S0377-0273(99)00179-1.

Rosi, M., 1998, Plinian eruption columns: Particle transport and fallout, *in* Freundt, A., and Rosi, M., eds., From magma to tephra: Modelling physical processes of explosive volcanic eruptions: Amsterdam, Elsevier, Developments in Volcanology, v. 4, p. 139–172.

Rymer, H., 1996, Microgravity monitoring, *in* Scarpa, R., and Tilling, R.I., eds., Monitoring and mitigation of volcano hazards: Berlin, Springer, p. 169–197.

Rymer, H., van Wyk de Vries, B., Stix, J., and Williams-Jones, G., 1998, Pit crater structure and processes governing persistent activity at Masaya volcano, Nicaragua: Bulletin of Volcanology, v. 59, p. 345–355.

Sapper, C., 1925, Los Volcanes de America Central: Halle, Germany, Max Niemeyer, 116 p.

Schilling, S.P., 1998, LAHARZ: GIS programs for automated mapping of lahar-inundation hazard zones: U.S. Geological Survey Open-File Report 98, 79 p.

Schmincke, H.U., 2004, Volcanism: Springer, Heidelberg, 324 p.

Scott, K.M., Marcias, J.L., Naranjo, J.A., Rodriguez, C., and McGeehin, J.P., 2001, Catastrophic debris flows transformed from landslides in volcanic terrains: mobility, hazard assessment, and mitigation strategies: U.S. Geological Survey Professional Paper 1630, 71 p.

Scott, K.M., Vallance, J.W., Kerle, N., Macias, J.L., Strauch, W., and Devoli, G., 2005, Catastrophic precipitation-triggered lahar at Casita volcano, Nicaragua: occurrence, bulking and transformation: Earth Surface Processes and Landforms, v. 30, p. 59–79, doi: 10.1002/esp.1127.

Scott, W., Gardner, C., Devoli, G., and Alvarez, A., this volume, The A.D. 1835 eruption of Volcán Cosigüina, Nicaragua: A guide for assessing local volcanic hazards, *in* Rose, W.I., Bluth, G.J.S., Carr, M.J., Ewert, J.W., Patino, L., and Vallance, J.W., Volcanic hazards in Central America: Geological Society of America Special Paper 412, doi: 10.1130/2006.2412(09).

Self, S., Rampino, M.R., and Carr, M.J., 1989, A reappraisal of the 1835 eruption of Cosigüina and its atmospheric impact: Bulletin of Volcanology v. 52, p. 57–65, doi: 10.1007/BF00641387.

Sheridan, M.F., Bonnard, C., Carreno, R., Siebe, C., Strauch, W., Navarro, M., Calero, J.C., and Truijilo, N.B., 1999, 30 October 1998 rock fall/avalanche and breakout flow of Casita volcano, Nicaragua, triggered by Hurricane Mitch: Landslide News, v. 12, p. 2–4.

Simkin, T., 1993, Terrestrial volcanism in space and time: Annual Reviews of Earth and Planetary Science, v. 21, p. 427–452, doi: 10.1146/annurev.ea.21.050193.002235.

Simkin, T., and Siebert, L., 2000, Earth's volcanoes and eruptions: An overview, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: New York, Academic Press, p. 249–261.

Smithsonian Institution, 2005, Smithsonian Global Volcanism Program, Worldwide Holocene Volcano and Eruption Information: Washington, D.C., National Museum of Natural History, www.volcano.si.edu (last accessed June 2006).

Sparks, R.S.J., 2003, Forecasting volcanic eruptions: Earth and Planetary Science Letters, v. 210, p. 1–15, doi: 10.1016/S0012-821X(03)00124-9.

Spence, R.J.S., Kelman, I., Baxter, P.J., Zuccaro, G., and Petrazzuoli, S., 2005, Residential building and occupant vulnerability to tephra fall: Natural Hazards and Earth System Science, v. 5, p. 477–494.

Stoiber, R.E., and Carr, M.J., 1973, Quaternary volcanic and tectonic segmentation of Central America: Bulletin of Volcanology v. 37, p. 304–325.

Sussman, D., 1985, Apoyo Caldera, Nicaragua: a major Quaternary silicic eruptive center: Journal of Volcanology and Geothermal Research, v. 24, p. 249–282, doi: 10.1016/0377-0273(85)90072-1.

Swanson, D.A., Casadevall, T.J., Dzurisin, D., Holcomb, R.T., Newhall, C.G., Malone, S.D., and Weaver, C.S., 1985, Forecasts and predictions of eruptive activity at Mount St. Helens, USA: Journal of Geodynamics, v. 3, p. 397–423, doi: 10.1016/0264-3707(85)90044-4.

Tilling, R.I., and Dvorak, J.J., 1993, Anatomy of a basaltic volcano: Nature, v. 363, p. 125–133, doi: 10.1038/363125a0.

Ui, T., 1972, Recent volcanism in Masaya-Granada area, Nicaragua: Bulletin of Volcanology v. 36, p. 174–190.

U.S. Environmental Protection Agency (EPA), 2005, Air trends: More details on sulfur dioxide, based on data through 2002: http://www.epa.gov/oar/airtrends/sulfur2.html (last accessed June 2006).

Valentine, G.A., 1998, Damage to structures by pyroclastic flows and surges, inferred from nuclear weapons effects: Journal of Volcanology and Geothermal Research, v. 87, p. 117–140, doi: 10.1016/S0377-0273(98)00094-8.

Valentine, G.A., and Fisher, R.V., 2000, Pyroclastic surges and blasts, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: New York, Academic Press, p. 571–580.

Vallance, J.W., 2000, Lahars, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: New York, Academic Press, p. 601–616.

Vallance, J.W., Schilling, S.P., Devoli, G., and Howell, M.M., 2001a, Lahar hazards at Concepción Volcano, Nicaragua: U.S. Geological Survey Open-File Report 01-457, 13 p.

Vallance, J.W., Schilling, S.P., and Devoli, G., 2001b, Lahar hazards at Mombacho Volcano, Nicaragua: U.S. Geological Survey Open-File Report 01-455, 14 p.

Van der Laat, R., 1996, Ground-deformation methods and results, *in* Scarpa, R., and Tilling, R.I., eds., Monitoring and mitigation of volcano hazards: Berlin, Springer, p. 147–168.

van Wyk de Vries, B., Kerle, N., and Petley, D.N., 2000, Sector collapse forming at Casita volcano, Nicaragua: Geology, v. 28, p. 167–170, doi: 10.1130/0091-7613(2000)028<0167:SCFACV>2.3.CO;2.

Voight, B., and Cornelius, R.R., 1991, Prospects for eruption prediction in near-real-time: Nature, v. 350, p. 695–698, doi: 10.1038/350695a0.

Voight, B., Glicken, H., Janda, R.J., and Douglass, P.M., 1981, Catastrophic rockslide avalanche of May 18, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 347–377.

Voight, B., Hoblitt, R.P., Clarke, A.B., Lockhart, A.B., Miller, A.D., Lynch, L., and McMahon, J., 1998, Remarkable cyclic ground deformation monitored in real-time on Montserrat, and its use in eruption forecasting: Geophysical Research Letters, v. 25, p. 3405–3408, doi: 10.1029/98GL01160.

Wadge, G., 1982, Steady state volcanism: Evidence from eruption histories of polygenetic volcanoes: Journal of Geophysical Research, v. 87, p. 4035–4049.

Walker, J.A., 1984, Volcanic rocks from the Nejapa and Granada cinder cone alignments, Nicaragua: Central America: Journal of Petrology, v. 25, p. 299–342.

Walker, J.A., Williams, S.N., Kalamarides, R.I., and Feigensohn, M.D., 1993, Shallow open-system evolution of basaltic magma beneath a subduction zone volcano: the Masaya caldera complex, Nicaragua: Journal of Volcanology and Geothermal Research, v. 56, p. 379–400, doi: 10.1016/0377-0273(93)90004-B.

Walker, J.A., Patino, L.C., Carr, M.J., and Feigenson, M.D., 2001, Slab control over HFSE depletions in central Nicaragua: Earth and Planetary Science Letters, v. 192, p. 533–543, doi: 10.1016/S0012-821X(01)00476-9.

Walther, C.H.E., Flueh, E.R., Ranero, C.R., von Huene, R., and Strauch, W., 2000, Crustal structure across the Pacific margin of Nicaragua: Evidence for ophiolitic basement and a shallow mantle sliver: Geophysical Journal International, v. 141, p. 759–777, doi: 10.1046/j.1365-246x.2000.00134.x.

Wehrmann, H., Bonadonna, C., Freundt, A., Houghton, B.F., and Kutterolf, S., this volume, Fontana Tephra: A basaltic Plinian eruption in Nicaragua, *in* Rose, W.I., Bluth, G.J.S., Carr, M.J., Ewert, J.W., Patino, L., and Vallance, J.W., Volcanic hazards in Central America: Geological Society of America Special Paper 412, doi: 10.1130/2006.2412(11).

Weinberg, R.F., 1992, Neotectonic development of western Nicaragua: Tectonics, v. 11, p. 1010–1017.

Weyl, R., 1980, Geology of Central America, *in* Bender, F., et al., eds., Beiträge zur regionalen Geologie der Erde (2nd ed.): Berlin–Stuttgart, Gebrüder Borntraeger, v. 15, p. 1–371.

Williams, S.N., 1983, Plinian airfall deposits of basaltic composition: Geology, v. 11, p. 211–214, doi: 10.1130/0091-7613(1983)11<211:PADOBC>2.0.CO;2.

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## Volcanic hazards in Nicaragua: Past, present, and future

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