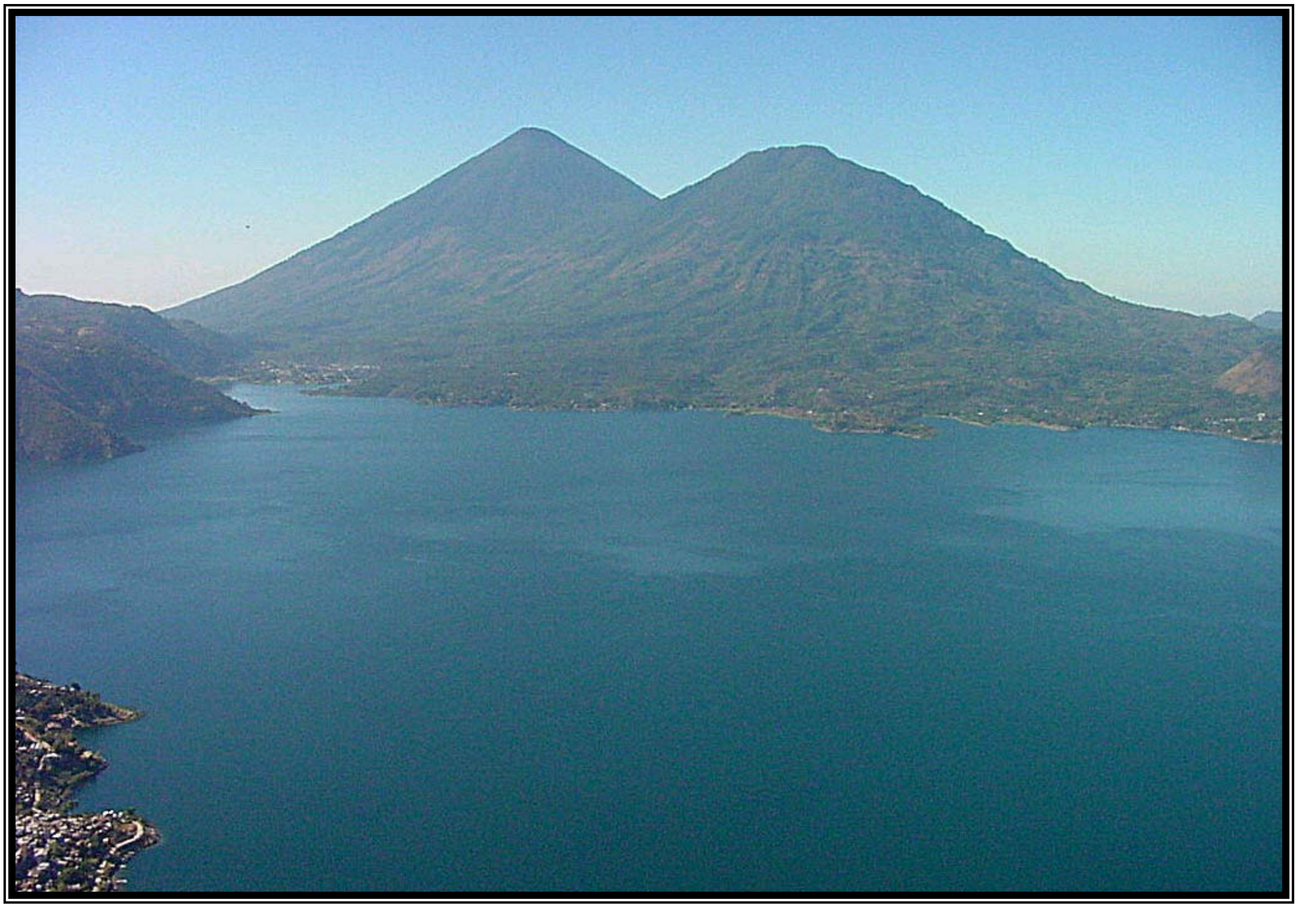
Volcanic Hazards at Atitlán Volcano, Guatemala



Open-File Report 2005-1403

U.S. Department of the Interior
U.S. Geological Survey

Cover Photograph

View of Atitlán and Tolimán Volcanoes from the northeast across Lake Atitlán. Photo by M. Mota.

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Introduction

Atitlán Volcano is in the Guatemalan Highlands, along a west-northwest trending chain of volcanoes parallel to the mid-American trench (figure 1). The volcano perches on the southern rim of the Atitlán caldera, which contains Lake Atitlán. Since the major caldera-forming eruption 85 thousand years ago (ka), three stratovolcanoes—San Pedro, Tolimán, and Atitlán—have formed in and around the caldera. Atitlán is the youngest and most active of the three volcanoes. Atitlán Volcano is a composite volcano, with a steep-sided, symmetrical cone comprising alternating layers of lava flows, volcanic ash, cinders, blocks, and bombs.

Eruptions of Atitlán began more than 10 ka [1] and, since the arrival of the Spanish in the mid-1400's, eruptions have occurred in six eruptive clusters (1469, 1505, 1579, 1663, 1717, 1826–1856). Owing to its distance from population centers and the limited written record from 200 to 500 years ago, only an incomplete sample of the volcano's behavior is documented prior to the 1800's. The geologic record provides a more complete sample of the volcano's behavior since the 19th century. Geologic and historical data suggest that the intensity and pattern of activity at Atitlán Volcano is similar to that of Fuego Volcano, 44 km to the east, where active eruptions have been observed throughout the historical period.

Because of Atitlán's moderately explosive nature and frequency of eruptions, there is a need for local and regional hazard planning and mitigation efforts. Tourism has flourished in the area; economic pressure has pushed agricultural activity higher up the slopes of Atitlán and closer to the source of possible future volcanic activity. This report summarizes the hazards posed by Atitlán Volcano in the event of renewed activity but does not imply that an eruption is imminent. However, the recognition of potential activity will facilitate hazard and emergency preparedness.

Volcanic Phenomena

Composite volcanoes like Atitlán Volcano erupt periodically and pose a variety of geologic hazards, not only during eruptions, but also during quiescent periods. All of the hazardous events depicted in Figure 2 have likely occurred at Atitlán Volcano in the past and will probably occur in the future. The eruptions of molten rock, or magma, caused most of these events. As with other composite volcanoes, the nature of activity has depended in part on the size and type of volcano, the composition of the magma, and interactions between magma and ground water. Some of these hazards, such as earthquakes, landslides and lahars, can also occur without warning during otherwise quiescent periods.

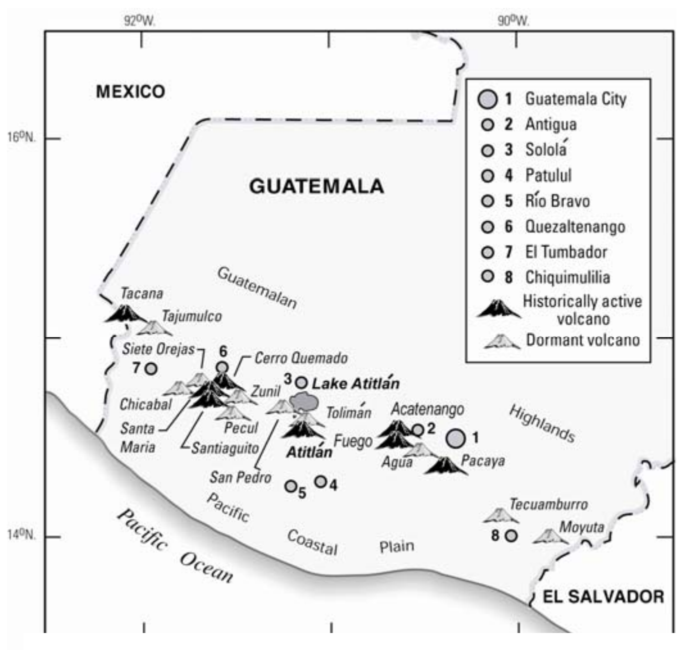

Figure 1. Location of major cities and major volcanoes.

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Hazardous Phenomena at Composite Volcanoes

Explosive **vulcanian** and **plinian** eruptions at Atitlán Volcano were observed during the activity of 1826 to 1856. Vulcanian and plinian eruptions form eruption columns that exit the vent at high velocity and rise high above the peak of a volcano. A vulcanian eruption has a short-lived eruption column and tephra plume commonly between 1 and 5 km high. Their eruptions comprise discrete and violent explosions that produce a high percentage of ballistic projectiles (figure 2). In contrast, a plinian eruption generates a continuous, convective column and tephra plume that can reach up to 20 km high. Plinian eruptions commonly generate pyroclastic flows, but have a small percentage of ballistic debris.

Tephra

As magma nears the surface of a volcano, it releases dissolved gases (e.g., water vapor, carbon dioxide, and sulfur dioxide) because of reduced pressure. The rapidly expanding gas causes solidifying magma to fragment into particles called **tephra**, which range in size from microscopic ash to meter-sized lava fragments. If hot ash particles erupt into the air, they heat the surrounding air and cause the ash plume to rise. Tephra from ash plumes falls downwind from the volcano and is deposited as broad lobes. The thickness and particle-size distribution of a tephra-fall deposit generally decreases with distance downwind from the vent. A tephra-fall deposit can cover areas of tens to hundreds of square kilometers. The largest tephra fragments, called ballistic bombs, fall to the ground within a few kilometers of the vent.

Tephra fall seldom threatens life directly, except within a few kilometers of the vent, where the impact of large ballistic fragments can cause death or severe injury. Large projectiles may be hot when they land and can start fires if they fall onto combustible material. Most injuries and fatalities from tephra falls occur when the tephra accumulations are 10 cm or more thick or are wet because of rainfall and heavy enough to collapse the roofs of buildings. Fine tephra suspended in the air can irritate eyes and lungs, especially among the elderly, infants, and those with pre-existing respiratory problems.

Indirect effects of tephra falls can be more disruptive. Tephra fall can create minutes to days of darkness, even on sunny days, and can greatly reduce visibility. Airborne ash ingested by jet engines can abrade parts and melt within the engine, potentially causing malfunction and power loss. Even small, dilute tephra clouds can damage jet aircraft that fly through them by clogging filters and increasing wear. Tephra can short-circuit electrical transformers and break power lines, especially if wet, and can contaminate surface water, plug storm drains and sewer systems, and clog irrigation canals. Even thin tephra accumulations may ruin crops if it contains acid precipitates or is heavy enough to break foliage. Tephra can add nutrients to soils and damage to crops typically does not extend for more than a few years.

Since Europeans settled in Guatemala, eruptions of Atitlán Volcano have repeatedly spread tephra deposits more than 90 km downwind. Tephra deposits can have thicknesses greater than 10 cm at distances as far as 20 km downwind. Distal tephra-fall deposits from Atitlán are predominantly fine ash. Near the source, tephra-fall deposits include numerous particles greater than one centimeter in diameter.

The activity from 1826 to 1856 included many eruptions that covered the coast near Suchitepequez and areas up to 50 km southwest of Atitlán Volcano with tephra. The eruption in 1853 was short but quite strong and caused complete darkness around Lake Atitlán for four hours [2].

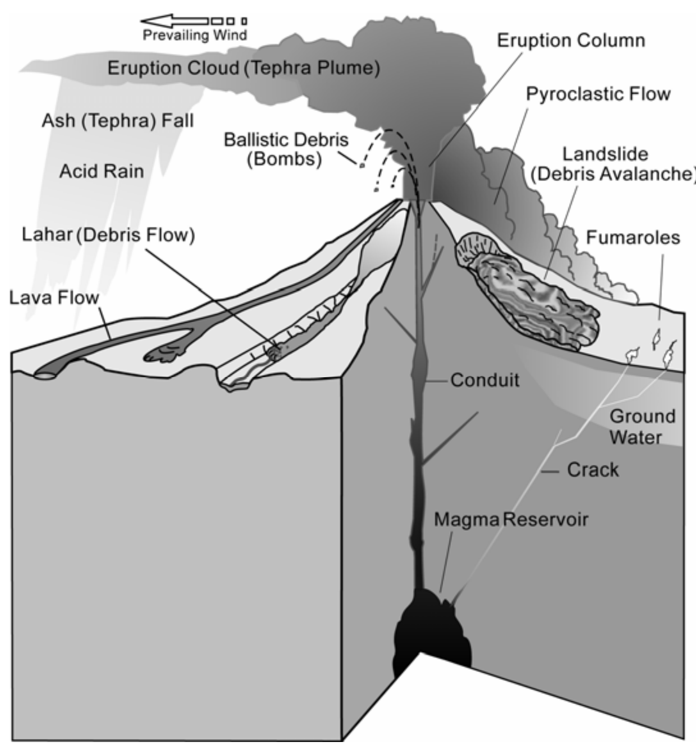

Figure 2. Hazardous events associated with composite volcanoes like Atitlán Volcano.

Pyroclastic Flows and Pyroclastic Surges

Sometimes the mixture of hot gases and ash to boulder-size fragments produced by an explosive eruption is more dense than air, and instead of rising above the vent to produce tephra, the dense mixture behaves like a fluid, staying close to the ground and moving down the slopes as an extremely hot **pyroclastic flow** (figure 2). If the mixture contains large amounts of particles, it will tend to funnel into topographically low areas, like barrancas and valleys. However, sufficiently voluminous flows or sequences of voluminous flows, especially on the slopes of the cone, may fill barrancas and sweep across fans in between them. Pyroclastic flows commonly destroy all structures and kill all living things in their paths.

Pyroclastic flows commonly generate dilute mixtures of hot ash and gas, called **pyroclastic surges**. These surges can separate from the pyroclastic flows and move over higher areas adjacent to or beyond the margins of the pyroclastic flow. Although pyroclastic surges may be somewhat less destructive to structures, they are lethal. Pyroclastic surges can also be produced directly by explosions from vents or from explosive collapse of domes. Pyroclastic surges can cause severe burns, trauma to the lungs, or suffocation. Temperatures of pyroclastic flows and surges can be several hundred degrees Celsius or more. These phenomena can move at speeds of 50 to 150 km per hour, thus people on foot cannot outrun them.

Pyroclastic flows have occurred at Atitlán in intervals of about 200 to 400 years. Pyroclastic-flow deposits occur on all slopes of Atitlán and at distances as far as 12 km from the cone. Pyroclastic flows can result from fragmentation of lava flows descending steep slopes or from explosive eruptions. On the west flank, 3-ka pyroclastic-flow deposits underlie portions of the village of Santiago Atitlán. Since about 2 ka, all pyroclastic flows have flowed down the south-southwest flanks of Atitlán. Between 1826 and the 1856, pyroclastic flows traveled up to 6 km down the Quebrada Maxanal, leaving a deposit that now underlies the area near Finca Mocá Grande. Thus future pyroclastic eruptions will likely affect the area on the southwest flank of the volcano. This area is heavily cultivated and encompasses numerous coffee and sugar cane fincas, many of which are within 6 km of the summit.

Lava Flows

A **lava flow** is formed if magma degasses enough before it reaches the Earth’s surface to erupt passively. Lava flows can also be formed by the accumulation of spatter at the summit. Lava flows are typically blocky and slow, moving downslope as bouldery streams of rock a few meters to tens of meters thick at speeds of tens of meters per hour to tens of meters per minute. Although lava flows can be extremely destructive, they are typically not life-threatening. People can usually move out of the path of an advancing flow. Nonetheless these flows are extremely unstable on the steep slopes of volcanoes like Atitlán and sometimes collapse to form avalanches of hot block or pyroclastic flows.

Lava flows have moved down all sides of Atitlán Volcano. Typically, such flows have not traveled more than 7 km. In historical time, lava flows on Atitlán have only flowed a few hundred meters from the summit of the volcano before collapsing to form pyroclastic flows.

Volcanic Gases

Volcanic gases released by magma during and between eruptions consist of steam, carbon dioxide, sulfur dioxide, hydrogen sulfide, and small amounts of other gases. Generally, volcanic gases dissipate rapidly downwind from the volcano, but within a few kilometers of a vent they can be dangerous, causing injury to the eyes and lungs. In closed depressions, denser-than-air gases, such as carbon dioxide, can accumulate and cause asphyxiation, or suffocation. Currently, volcanic-gas hazards at Atitlán are confined to the summit area and crater. Fumaroles at the summit of Atitlán primarily release water vapor, which is formed as atmospheric moisture percolates into the ground, reaches warm rocks, and is converted to steam. In case of resumed activity at Atitlán, higher volumes of noxious gases will be released increasing the hazard beyond the summit area.

Debris Avalanches

Sector collapse of a volcano (or when a portion of the edifice collapses) can generate an unsaturated mixture of debris, rock, and water, called a **debris avalanche**, that can attain speeds in excess of 150 km per hour. The slopes at Atitlán Volcano are steep and can be unstable in times of heavy rain and seismic activity. In the past decade, a few small-scale debris avalanches, or landslides, have occurred on the east flanks of Atitlán Volcano because of nearby tectonic earthquakes. In prehistoric time, at least one debris avalanche occurred at Atitlán Volcano. Hummocks indicative of debris-avalanche deposits occur as far as 20 km from the summit to the south and southwest (figure 3). Magma intrusion can also cause slope instability and deep-seated failure. A slope failure and debris avalanche caused by magma intrusion from Atitlán seems unlikely compared to other hazards, since only one has occurred in the past ten thousand years.

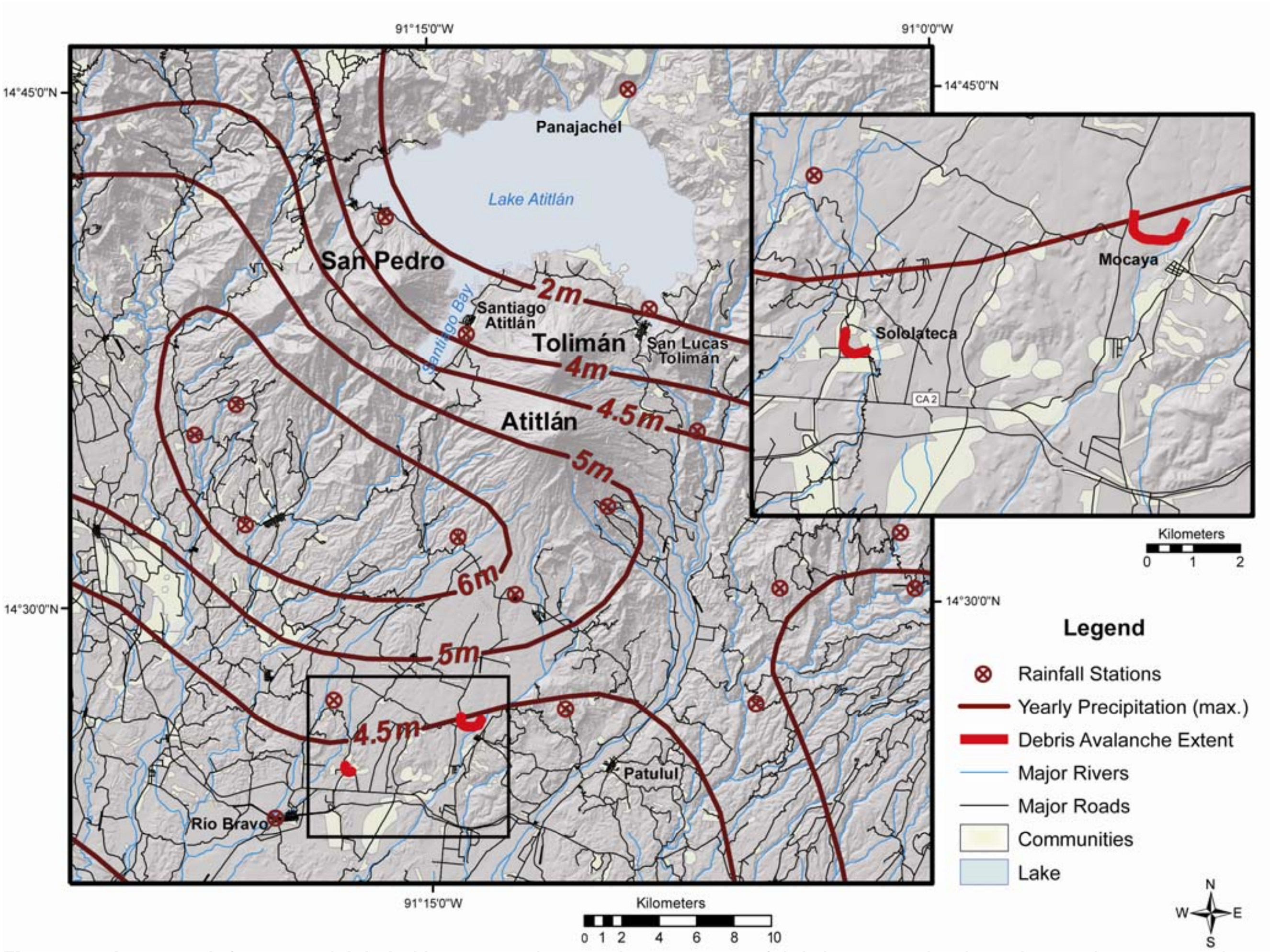

Figure 3. Annual rainfall around Atitlán Volcano and approximate extent of debris avalanche deposits. In the area southwest of Atitlán the total yearly rainfall is nearly 5 m.

Slope failures triggered by tectonic earthquakes, torrential rains, and steam explosions are commonly orders of magnitude smaller in volume than those triggered by magmatic intrusion. Small-volume debris avalanches typically travel only a few kilometers from their source, but large-volume debris avalanches can travel tens of kilometers from a volcano. They destroy everything in their paths and even small debris avalanches can leave deposits up to 10 m thick, and larger debris avalanches commonly leave deposits that are more than 100 m thick on valley floors.

Lahars

Lahars, also called mudflows and debris flows, are saturated mixtures of mud, rock, and water that flow down slope under the influence of gravity and look much like flowing concrete (figure 2). Lahars are particularly hazardous because they travel farther from a volcano than any other hazardous phenomenon, except tephra, and affect stream valleys where population density is usually greatest. They occur when water mobilizes large volumes of loose mud, rock, and volcanic debris. During periods of intense rainfall, landslides and avalanches commonly incorporate enough water to form lahars. Lahars primarily follow river valleys and like floods inundate floodplains and submerge structures in low-lying areas. They can travel many kilometers at speeds of tens of kilometers per hour, leaving deposits of muddy sand and gravel that can be several meters thick and destroying or damaging structures in their paths through burial or impact.

The amount of water and loose volcanic debris determines lahar size. Smaller lahars occur every few years, whereas larger lahars occur on a frequency of the order of centuries to millennia. Larger lahars tend to follow eruptions when heavy rains mobilize loose, recently deposited tephra or pyroclastic-flow deposits. Eruptions can deposit millions of cubic meters of sediment onto the flanks and into channels heading on the volcano that, when mixed with water during subsequent rains, cause lahars.

Once lahar deposits fill a stream channel with sediment, the stream begins to erode a new path. These new channels can be highly unstable and shift rapidly as sediment is eroded and carried farther down the valley. Also, stream channels clogged with sediment are less able to convey water and are more susceptible to flooding. Flood and lahar hazards can persist from years to decades after eruptions. In some instances, lahars clog channels or block tributaries forcing water to collect behind the blockage. The impounded water can spill over the blockage, quickly cut a channel, and catastrophically drain the water, generating a flood that moves down the valley. Breaching of such blockages may occur within hours or even months after impoundment.

Tsunamis

Tsunamis, or large waves, are caused by the sudden introduction of a major rock mass into a water body or by underwater earthquakes. Three thousand years ago, pyroclastic flows traveled down the western flanks of Atitlán Volcano and reached the current shores of Lake Atitlán. More voluminous pyroclastic flows or debris avalanches on the western flank of Atitlán could rapidly inundate shorelines around Santiago Bay and generate tsunamis that pose a hazard to inhabitants across the bay from the town of Santiago Atitlán.

Past Events at Atitlán Volcano

Atitlán Volcano is the only historically active volcano in the area around Lake Atitlán. Eruptions at Atitlán occur in clusters and can last for more than two decades. Geologic evidence indicates that the episodic volcanism at Atitlán has occurred during the last 10 ka, with the last eruptive episode occurring between 1826 and 1856 (figure 4). Six explosive historical clusters (AD 1469, 1505, 1579, 1663, 1717, and 1826–1856) are known, though other undocumented historical eruptions may have occurred. The historical observations of volcanism at Atitlán Volcano have been supplemented with radiocarbon dates from carbonized wood collected from pyroclastic-flow deposits.

Lake Atitlán inundates parts of several flank lava flows on both San Pedro and Tolimán Volcanoes, which indicates that the lake level has risen since the onset of activity at Atitlán Volcano. Lava flows, and more recently pyroclastic flows, from Atitlán Volcano blocked the outlet of the lake, which was located just south of the town of San Lucas Tolimán. A 30-m-high saddle now prevents surface out-flow from the lake. About 3 ka, explosive eruptions produced pyroclastic flows that descended the flanks to the west toward Santiago Atitlán. Also, during the same time period, pyroclastic flows traveled down the eastern flanks of Atitlán to just beyond the main road, RN11. According to diving records ancient ruins from Mayan and pre-Mayan cultures occur in Santiago Bay. The presence of these ruins and the dating of deposits in these areas suggest that Atitlán volcano produced lava flows and pyroclastic flows that dammed the lake outlet within the last 3000 years.

The activity at Atitlán from the 1400's through 1856 included explosive vulcanian and subplinian eruptions about every 100 years. Little is documented about the type of activity from Atitlán during this time period. Existing records document that sustained columns were produced and significant amounts of tephra were erupted in 1469 and 1505, and an eruption is recorded in 1663. Mudflows accompanied the later two eruptions, 1505 and 1663, as well as those in the 1800's. The eruptive episode in the 1800's produced lava flows, pyroclastic flows, low-intensity explosive activity, and lahars during nine different eruptive events. In 1827, a lava flow developed and a plinian column formed, depositing large volumes of tephra downwind. Another lava flow, largely confined to the central vent, occurred in 1843 and a plinian column developed during the 1853 activity. These eruptions in the 1800's also produced large pyroclastic flows that traveled to the south-southwest and are radiocarbon dated at about 200 years ago. Tephra falls, mudflows, and/or pyroclastic flows in 1827, 1833, and 1853 damaged structures and injured people living and working in the area. Eruptive events are also recorded in 1826, 1837, 1852, and 1856. On the basis of Atitlán's geologic record, the volcano can produce voluminous pyroclastic eruptions which are dangerous to those living in the area.

Most recently during quiescent periods, earthquakes and heavy rains have triggered lahars on unstable slopes of Atitlán Volcano. In 1991, the Pochuta earthquake triggered two major landslides and in 1998, heavy rain associated with Hurricane Mitch triggered a landslide near Cerro Tamalaj. On September 12, 2002, a two-hour period of heavy rain caused a debris flow on the eastern slope of Atitlán Volcano. This lahar was triggered in the late evening, traveled through two small communities, and damaged the main roadway connecting the lake communities to the coastal highway (figure 5). As a result of the lahar, several buildings were damaged, twenty-two homes destroyed, and thirty-seven people killed. This lahar flowed 7 km and had an estimated volume between 50,000 and 100,000 m^3. It occurred without warning, except for the heavy rainfall, and destroyed everything in its path.

Early in the morning of October 5, 2005 a lahar generated by heavy rainfall from Hurricane Stan, a

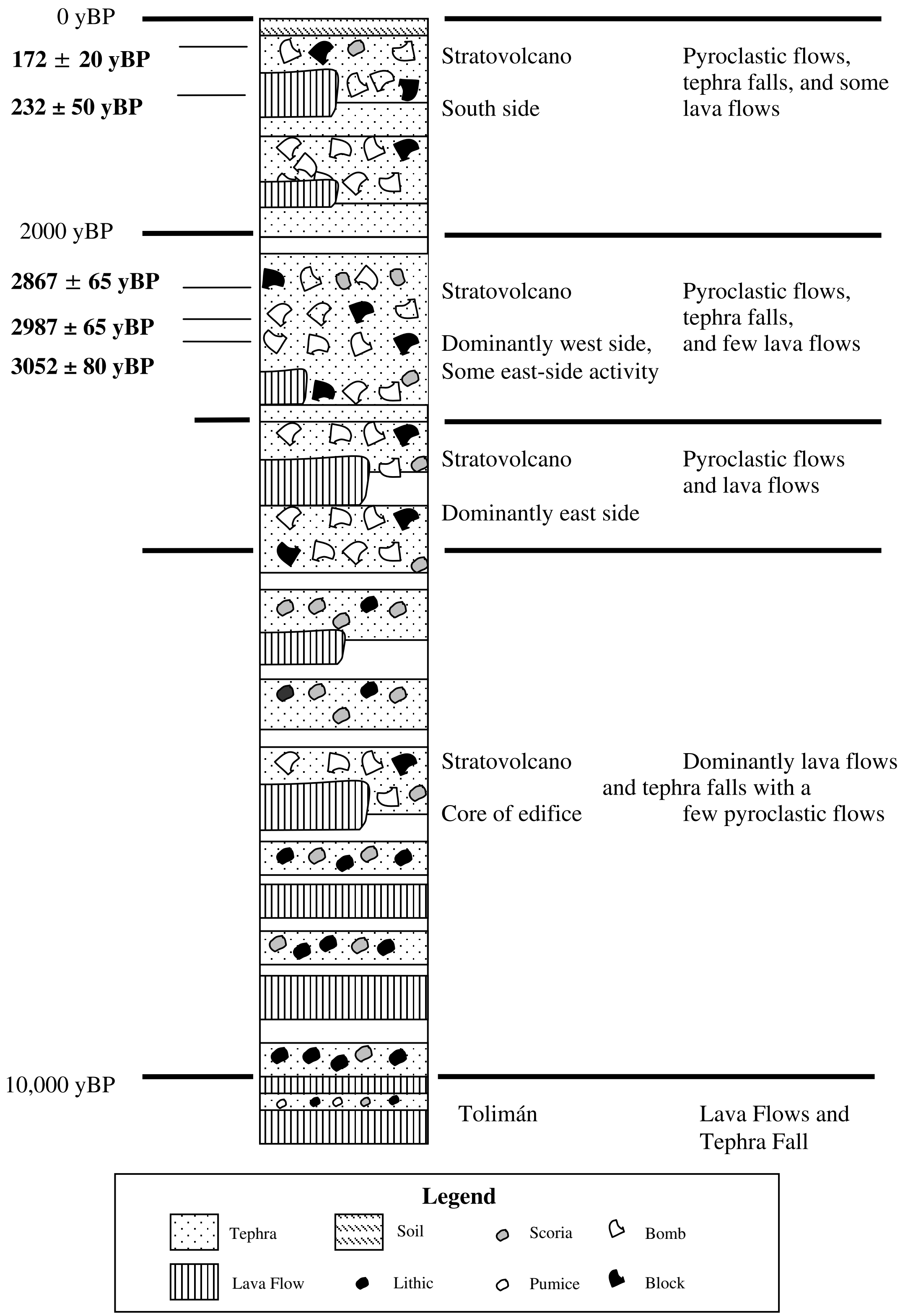

Figure 4. Simplified composite section and summary of eruptive history of Atitlán Volcano.

category-1 storm, destroyed the town of Panabaj and buried hundreds of people. As of October 10 at least 200 had died and hundreds more were missing. Panabaj is situated on a fan on the northwestern slopes of Atitlán volcano and is formed of pyroclastic-flow and lahar deposits. Heavy continuous rains between October 4 and October 8 caused numerous mudslides and debris flows throughout the Guatemalan highlands. Flooding knocked out key highway bridges and hampered rescue efforts. Lahars generated during heavy rains are likely to affect this fan and others like it in the future.

To the southeast of Atitlán along Río Madre Vieja, around 8,000 people live in the town of Patulul and surrounding fincas. Many of these communities are built on lahar deposits and lahar-transported boulders of up to 1 m in diameter are scattered throughout the area. In the southern reaches of the Río Bravo drainage, around 20 km south of Atitlán, the community of Río Bravo (population 5,000) is also underlain by lahar deposits containing 1-m diameter boulders. Lahars will likely affect these south-southwest areas during and following future eruptions of Atitlán Volcano and during periods of heavy rain.

Potential Future Activity at Atitlán Volcano

As stated above, future activity at Atitlán threatens numerous communities around Atitlán Volcano with a wide array of activity including tsunamis, lahars, pyroclastic flows, tephra fall, lava flows, and debris

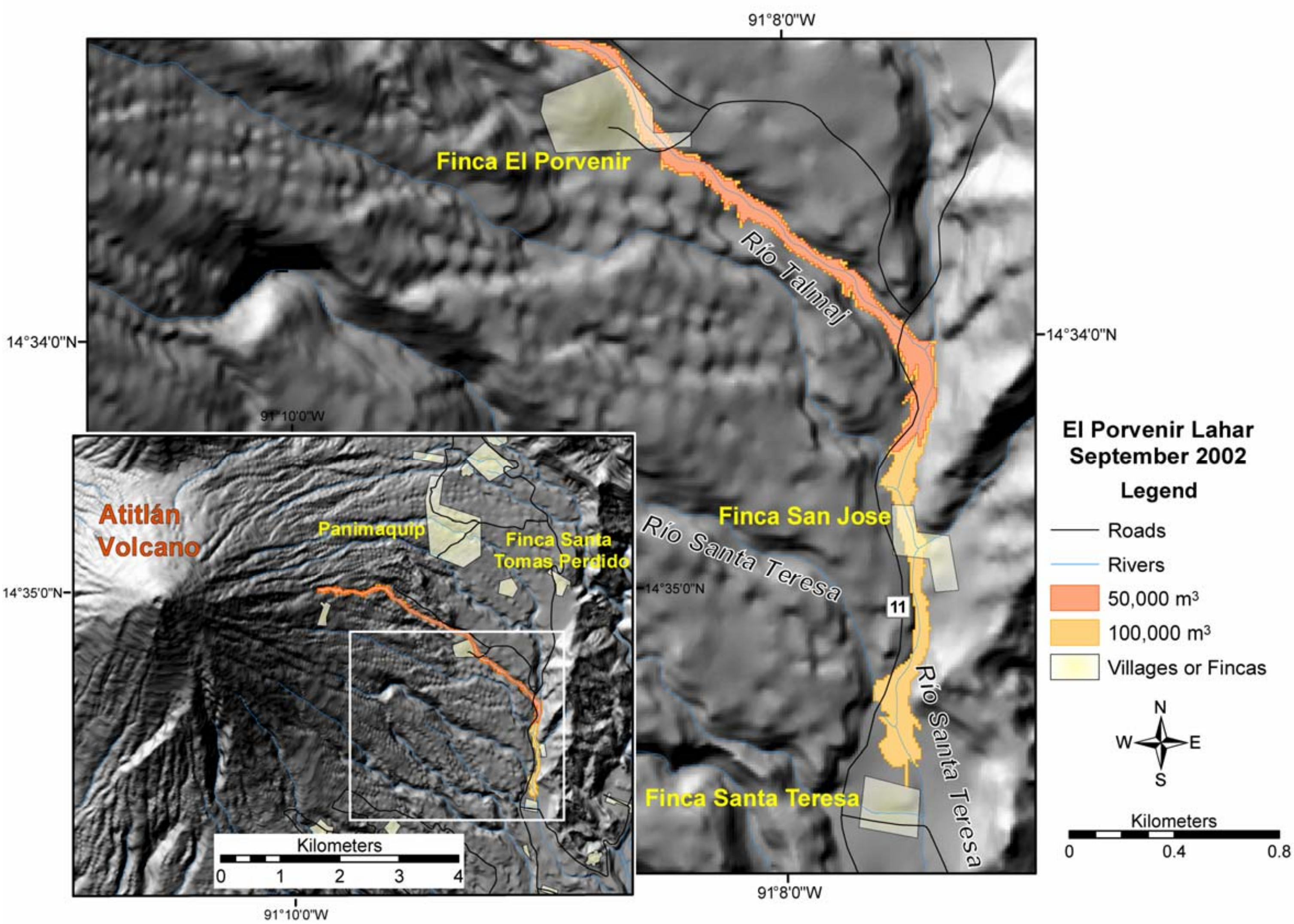

Figure 5. Computer model of the September 2002 El Provenir lahar.

avalanches. An agricultural area of about 180 km^2 around Atitlán is underlain by historical pyroclastic-flow deposits. The region has a population of around 12,000 people living on fincas and in small villages. Outside of this area and to the west, Santiago Atitlán, a town of 17,000 people, is threatened by tsunamis caused by a sudden influx of a large mass of material to the Santiago Bay. San Lucas Tolimán, a community of 8,000 people less than 10 km to the northeast, is in a potential pyroclastic-surge- or lahar-hazard zone. Currently, only a 30-m-high saddle protects San Lucas Tolimán from pyroclastic surges and extremely large lahars from Atitlán Volcano. Similar small barriers were overtopped by lahars at Santiaguito Volcano in the 1980s.

Potential Future Eruption by Comparison to Fuego Volcano

On the basis of historical accounts, and field work, events similar to those at nearby Fuego have occurred in Atitlán's past and will likely occur at Atitlán in the future. Deposits indicate that Atitlán, like Fuego, has produced tephra, pyroclastic flows, lahars, and lava flows. Recognition of the similarity of Atitlán and Fuego is important, because Fuego's recent eruptions (i.e., 1966, 1973, 1974, 1999, and 2002–3) are familiar through direct observations of the eruptions during the past four decades.

On the basis of past activity and the comparison to Fuego Volcano, future volcanism will largely comprise moderate to moderately-strong eruptions. These stronger eruptions may include pyroclastic flows that could move up to 15 km from the source and tephra falls that could blow up to 100 km downwind. Less explosive eruptions will form lava flows that could move a few kilometers from their source. A debris avalanche could be triggered by shallow intrusions of magma or by explosions. Although it is of very low probability, a debris avalanche could flow up to 30 km to the south and destroy everything in its path. Heavy rainfall would remobilize the fresh pyroclastic material in the form of lahars. These lahars would move up to 30 km from the volcano to the south. Lahars would happen soon after an eruption and could be a persistent hazard for years following the eruption. Deposition of laharic and pyroclastic debris increases the chance for flooding, which in turn can damage infrastructure and inconvenience people in populated areas downstream of the volcano.

Volcano-Hazard-Zonation Maps

The accompanying volcano-hazard-zonation maps (plate 1) show areas that could be affected by future events at Atitlán Volcano. Individual events typically affect only part of a hazard zone. The location and size of an affected area will depend on the location of the erupting vent or landslide scarp, the volume of material involved, and the character of an eruption, especially its explosivity.

Potentially hazardous areas around Atitlán Volcano include proximal and distal lahar-hazard zones and tephra-fall-hazard zones, and pyroclastic-flow- and lava-flow-hazard zones (plate 1). Some hazard zones are subdivided on the basis of their relative degree of hazard. Three methods determine hazard-zone boundaries. First, the magnitudes of each type of event are inferred from historical accounts and prehistoric deposits. Second, for lahar-hazard zones, an empirical model estimates lahar-inundation limits on the basis of lahars of known volumes that have occurred at other volcanoes. Finally, experience and judgment derived from past events of similar nature at other volcanoes is applied.

Although sharp boundaries delineate each hazard zone, the limit of the hazard does not end abruptly at the boundaries. Rather, the hazards decrease gradually as distance from the volcano increases and, for lahars, decreases rapidly with increasing elevation above valley floors. Areas immediately beyond distal hazard zones are not hazard-free because the limits can be located only approximately, especially in areas of low relief. Many uncertainties about the source, size, and mobility of future events preclude precise location of the boundaries of hazard zones.

Users of the hazard maps should be aware that not all potentially hazardous landslide- and lahar-prone areas have been modeled. Atitlán Volcano is steep, carved by water, and in some areas partly affected by hydrothermal weakening of the rock. For this report, prominent channels selected for modeling were those directed toward populous areas in order to define the most significant impacts of inundation from lahars of various volumes. Other channels for which lahar inundation was not modeled are not necessarily devoid of lahar hazard. Landslides and lahars from other channels could also threaten life and property.

Proximal Lahar-Hazard Zones

The proximal lahar-hazard zone includes areas immediately surrounding Atitlán Volcano and delineates areas where lahars and avalanches originate. It extends about 3 to 4 km from the summit depending upon local topography. During periods of volcanic unrest or an eruption, this area should be evacuated because events (i.e., pyroclastic flows, lava flows, debris avalanches, and lahars) can occur too quickly for humans to escape harm. Small landslides and mudflows may be restricted to the proximal lahar hazard zone. However, large debris avalanches and lahars will travel away from the volcano and onto adjacent slopes beyond the proximal lahar hazard zone. The extent of inundation from these larger lahars is the basis for defining distal lahar-hazard zones.

Distal Lahar-Hazard Zones

An automated empirical technique calibrated with data from other volcanoes estimates potential areas of inundation from lahars of various volumes. For each channel analyzed, there are five to six nested hazard zones defined, which depict anticipated inundation by hypothetical "design" lahars having different volumes. The largest design lahar reflects an estimate of the largest probable lahar that could be generated. The smallest and intermediate volume design lahars are more typical for other volcanoes studied, with volumes of 1, 2, 4, and possibly 8 million cubic meters, and have occurred at Atitlán after eruptions or during severe rainstorms.

Large lahars are less likely to occur than small lahars. Thus, the nested lahar-hazard inundation zones show that the likelihood of lahar inundation decreases as distance from the volcano and elevation above the valley floor increases. Although it appears on Plate 1, no lahar as voluminous as 16 million cubic meters has occurred historically at Atitlán Volcano. Nonetheless, after eruptive clusters like that of 1826–1856, floods and aggradation due to upstream lahar deposit have affected areas as far downstream as the distal margins of the 16-million-cubic-meter zone. The coastal road (CA-2) crosses the Ríos Bravo, Corallio, Madre Vieja, and Mocá 20 km south of Atitlán Volcano. All of these rivers contain substantial lahar deposits to the limit of the 16-million-cubic-meter lahar-inundation zone. On the basis of data collected since the mid-fifteenth century, inundation in the most distal area occurs about once every one to two hundred years, about equal to the probability of larger eruptions. Large lahars are more likely to occur following explosive eruptions and smaller lahars will probably occur for several years following an eruption. Local finca owners have observed that small-scale lahars occur about twice a decade.

After eruptions, drainages south of Atitlán might be filled with volcanic sediment from lahars and pyroclastic flows and change course suddenly. Lahar hazards associated with the new channel are greatly increased compared to the old channel. Hazards in drainages heading on the volcano are greater than in neighboring drainages, and decrease with distance downstream.

Heavy Rain-Induced Lahars

Lahars of all modeled sizes could form and travel down the volcano's slopes if unusually intense rainstorms occur. The heaviest rainfall rates are nearly all associated with hurricanes and occur during the monsoon season (figures 6 and 7). Subtropical hurricanes have affected the area at least seven times in the last 80 years (approximately once per decade).

The annual rainfall on the Atitlán Volcano averages around 3m/year but ranges from about 1 m/yr to more than 5 m/yr on the south side, which receives the greatest amount of rain (figure 3). The highest average daily rainfall rate over the last 30 years was 556 mm/day measured at Mocá Suchitpezuez, a rainfall station on the southwest flanks of Atitlán Volcano. Peak rainfall occurs at elevations of about 500 to 2000 m.

Hurricane-induced lahars have occurred at volcanoes similar to Atitlán. On October 30, 1998, several days of intense rain from Hurricane Mitch triggered a slope failure on the south side of Casita Volcano, in Nicaragua. The debris avalanche, in turn, generated a lahar of 2 to 4 million cubic meters that swept down the south side of the volcano and spread out on the aprons of the volcano, destroying two towns and killing about 2,500 people. A similar event occurred at Agua Volcano in Guatemala on September 11, 1541. Heavy rains caused a debris flow that destroyed the capital city, Cuidad Vieja (old Guatemala City), killing more than 600 people, and the capital was relocated. The debris flows at Agua in 1541 and Casita in 1998 both occurred in the latter half of the rainy season, when the ground was water saturated, and several days of heavy rain triggered a landslide which produced the lahars. An intense storm, like Hurricane Mitch, centered at Atitlán, could trigger large-scale lahars. Smaller lahars have and may occasionally result from rainy-season (May to November) heavy rains.

Pyroclastic-Flow and Lava-Flow-Hazard Zones

The pyroclastic-flow and pyroclastic-surge hazard map in Plate 1 is based on the distribution of pyroclastic-flow deposits. The pyroclastic-surge hazard zone includes areas beyond the margins of the pyroclastic-flow-hazard zone that may be affected when a pyroclastic surge detaches from a pyroclastic flow.

The lava-flow-hazard map in Plate 1 was developed from the mapping of lava-flow deposits. North-traveling flows have been and will be diverted to the east and west by the slopes of Tolimán Volcano. Recent lava flows have not traveled more than a kilometer or two from the summit; however, in the past lava flows have affected all of the depicted area.

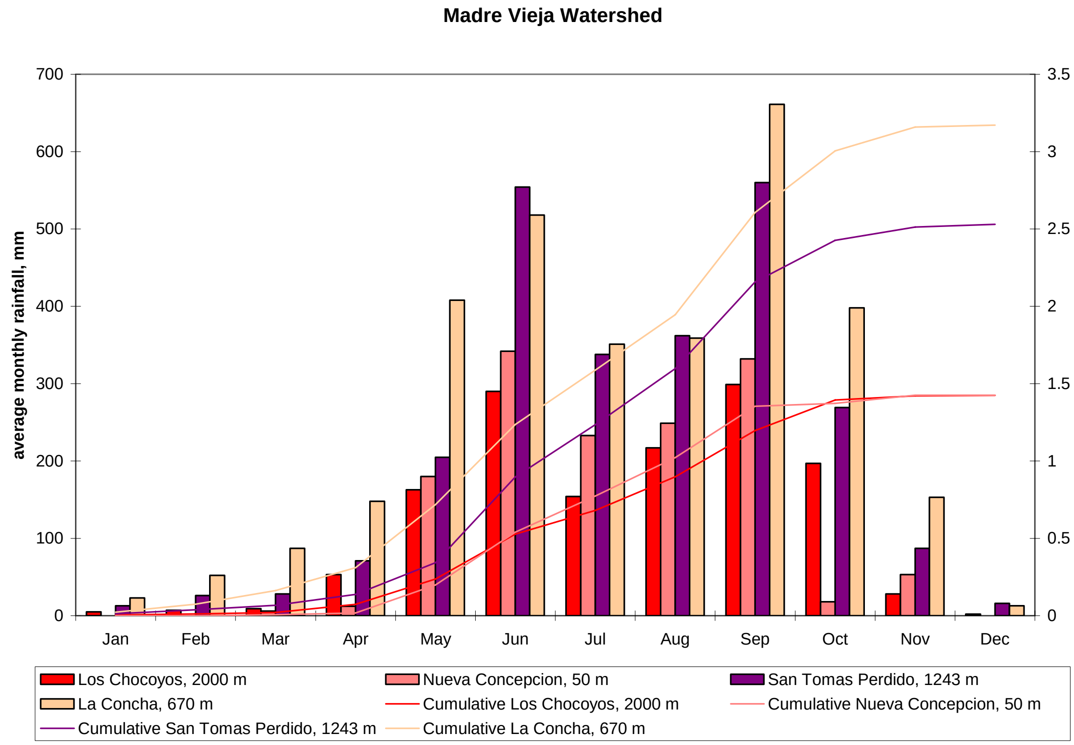

Figure 6. Monthly precipitation of stations for Río Madre Vieja the main drainage system on the eastern slopes of Atitlán Volcano.

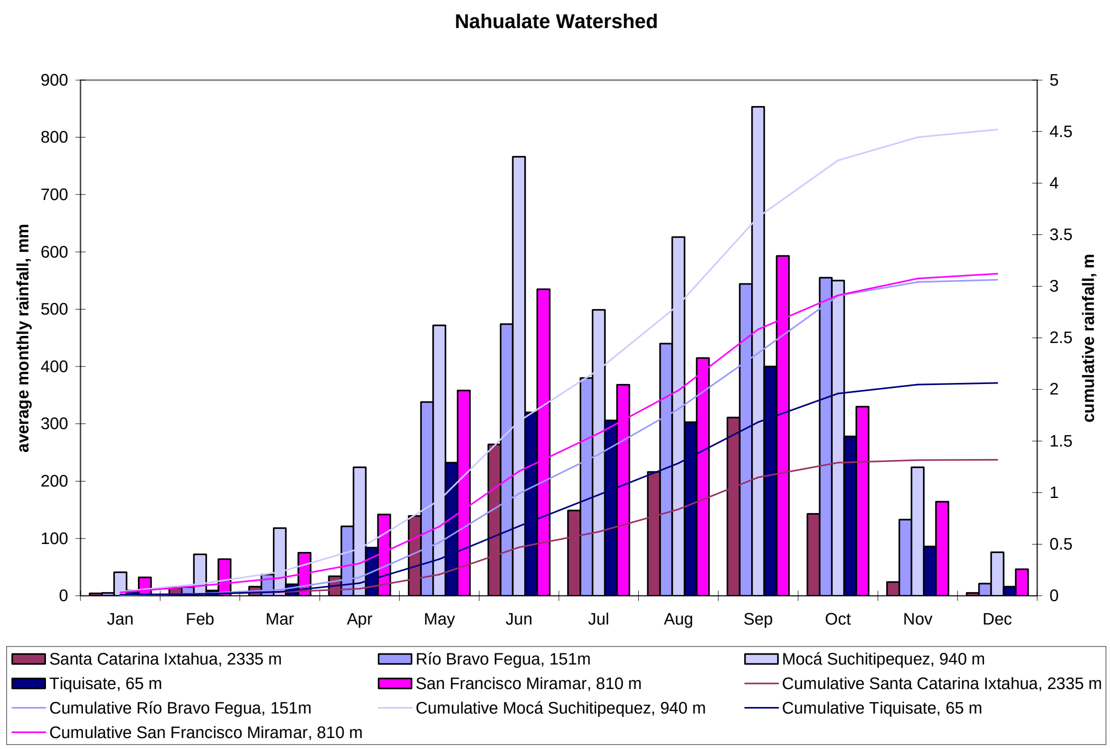

Figure 7. Monthly precipitation of stations for Río Nahualate the main drainage system on the western slopes of Atitlán Volcano.

A single pyroclastic flow, pyroclastic surge, or lava flow during an eruptive episode will not cover the entire area depicted in the pyroclastic-flow, pyroclastic-surge and lava-flow maps, but any one event can reach the outer limit of this area.

Tephra-Fall-Hazard Zones

In order to establish tephra-fall hazard zones, wind patterns and typical eruption sizes were identified. An average monthly wind-direction pattern covering the last six years was derived from wind data from the National Oceanic and Atmospheric Administration. The months of November through April, the dry season, are characterized by shearing lower-level winds and upper-level winds. Between ground level and around 3100 m, winds are from the northeast. Wind direction is variable from 3100 m to around 9000 m. Above 9000 m the wind is strongly from the southwest. This wind pattern is most consistent from January through March. Between May and October, the wet season, the wind pattern is from the east at all levels. This wind pattern is most consistent from June through August. Because April, May, October, and November are transitional months, some variability in wind direction at all levels exists.

Tephra will most likely travel east to east-southeast in the months of December through April and west to west-southwest in the months of May to November (figure 8). However, tephra can travel in the other low probability wind directions at any time of the year.

Tephra deposits of the volume modeled are possible, but lower volume tephra falls can occur more frequently. On the basis of past behavior, eruption of a tephra volume of 0.01 km^3 is likely to occur multiple times during an eruptive episode, whereas the eruption of a tephra volume of 0.2 km^3 of tephra has occurred in less than half of the historical eruptions.

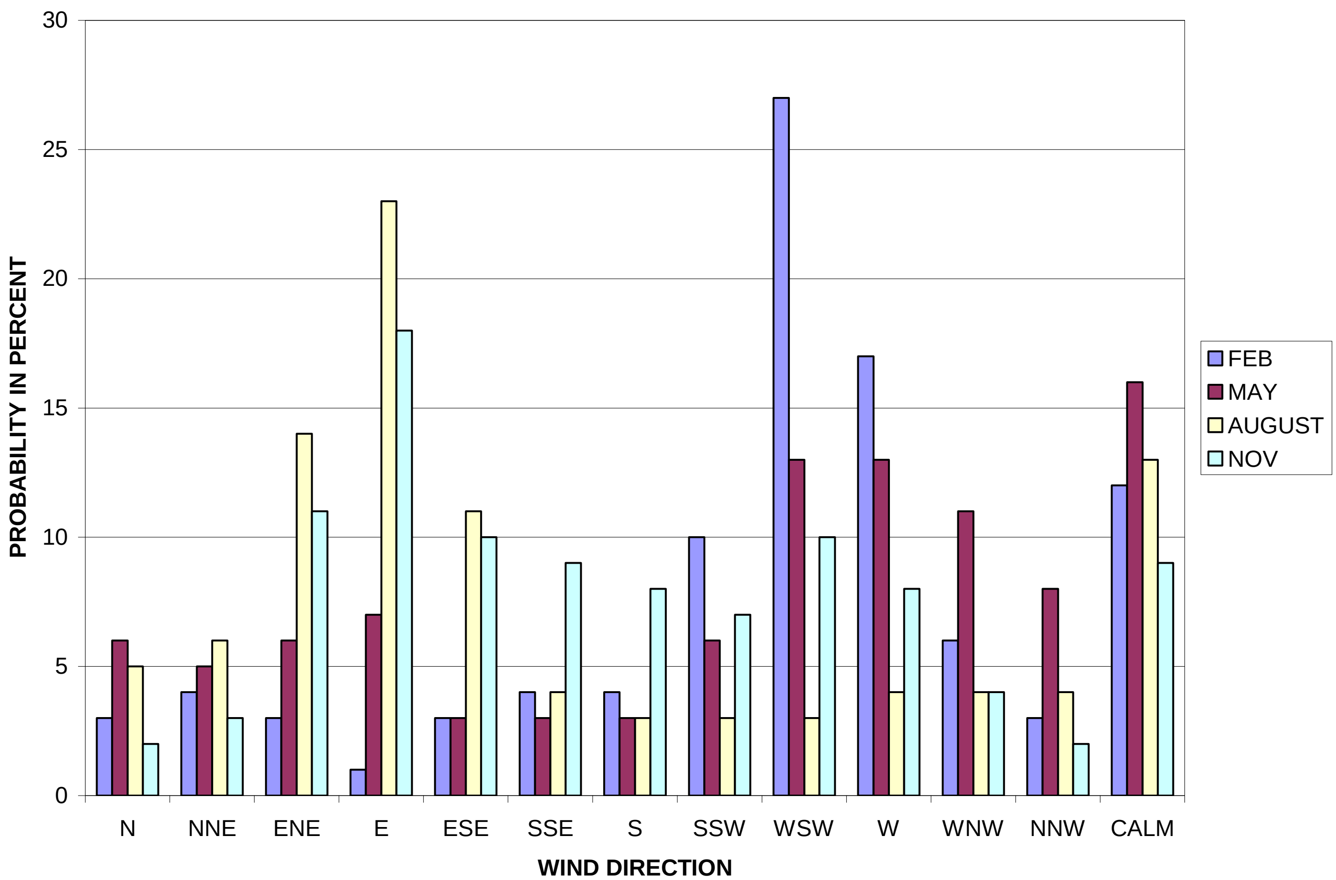

Figure 8. Map showing the probability of wind directions between 10,000 and 50,000 feet for Guatemala (Data from NOAA 40-km soundings). February directions are typical of the dry season from December though May and August directions are typical of wind directions for the rainy season from June to December. The directions given here are those in which the tephra plume will probably move rather than directions from which the wind moves.

Debris-Avalanche Hazard Zones

The probability of recurrence of a debris avalanche is very low. Nonetheless, understanding that such an event could occur is important because debris avalanches can travel great distances, cover huge areas, and destroy everything in their paths. Volcanic unrest and deformation of the edifice are likely to precede a voluminous deep-seated debris avalanche. A large debris avalanche could travel up to 30 km or more, a distance similar to those of past events at Atitlán, and similar to prehistoric events at Fuego. Small debris avalanches are likely to be confined to the proximal hazard zone or to lahar pathways.

Hazard Forecasts and Warnings

Scientists can monitor and recognize indicators of impending volcanic eruptions. The movement of magma into a volcano prior to an eruption causes changes that can usually be detected by geophysical and visual observations. Swarms of small earthquakes are generated as rock fractures to make room for rising magma or as heating of fluids increases underground pressure. Heat from magma can raise the temperature of groundwater, increase steaming from fumaroles; and occasionally generate small steam explosions. The composition of gases emitted by fumaroles changes as magma nears the surface. Injection of magma into the volcano can also cause ground swelling or other types of surface deformation.

The Guatemalan government plans to install a seismometer near Atitlán, and others have been installed near Fuego and Santa María. The country is developing a seismic network, so a significant increase in volcanigenic earthquakes at Atitlán Volcano would be noticed quickly. However, it is important to consider that Tolimán, San Pedro and the caldera are all plausible sources for such earthquakes.

Periods of unrest at volcanoes produce great social uncertainty. During the past few decades, substantial advances have been made in volcano monitoring and eruption forecasting, yet scientists often can make only very general statements about the probability, type, and scale of an impending eruption. Precursory activity includes accelerating and decelerating phases, and sometimes dissipates without an eruption. Government officials and the public must realize the limitations in forecasting of eruptions and must be prepared to cope with such uncertainty.

Despite advances in volcano monitoring and eruption forecasting, it is still difficult, if not impossible, to predict the precise occurrence of slope failures triggered by earthquakes or torrential rains. Therefore, potentially lethal lahars can, and most likely will, occur again at Atitlán Volcano with little or no warning. Thus, government officials and the public need to recognize the locations and limits of lahar-hazard zones.

Protecting Communities and Citizens from Volcano-Related Hazards

Public officials, business owners, and other citizens need to aid in mitigating the effects of future volcanic eruptions, debris avalanches, and lahars from Atitlán Volcano. Long-term mitigation efforts must include using information about volcanic hazards when making decisions about land-use and locating critical facilities (e.g., evacuation sites and hospitals). Hazard zones should influence where future development is appropriate.

Because a volcanic eruption can occur within weeks to months after the first precursory activity, and because some hazardous events, such as landslides and lahars, can occur without warning, a well-coordinated suitable emergency-response plan needs to be made in advance. Response will be most effective if citizens and public officials have a basic understanding of volcanic hazards and have planned the actions needed to protect communities.

Public officials should consider issues such as public education, communication, and evacuation as part of an emergency-response plan. Emergency plans already developed for floods apply to some extent, but need modifications for hazards associated with pyroclastic flows and lahars. Especially important is a plan of action based on the knowledge of relatively safe areas around homes, schools, and workplaces.

Lahars pose the biggest threat to people living or recreating along the channels that drain Atitlán Volcano. The best strategy for avoiding a lahar is to move to the highest possible ground. A safe height above river channels depends on many factors including the size of the lahar, distance from the volcano, and shape of the valley.

Atitlán Volcano will erupt again leading to tephra fall, pyroclastic flows, lava flows, lahars, and/or debris avalanches. The area around the volcano is also prone to slope failures and mudflows caused by seismic activity and heavy rains. The best way to cope with volcanic hazards, as with any hazard, is through advance planning of emergency response and, for the long term, consideration of volcanic hazards in future land-use and facility location in order to mitigate the effects of the potential activity at Atitlán Volcano.

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End Notes

[1] The age of Atitlán Volcano is at most a few tens of thousands years old based on stratigraphic sequences and comparison to other volcanoes in the Guatemalan chain. Atitlán tephra sequences numerous lava flows, and pyroclastic flows around the volcano occur stratigraphically above an Atitlán caldera tephra dated at 40 ka. The age of the volcano also derives from comparison to other active volcanoes in Guatemala such as Santa María Volcano inferred to be less than about 30 ka (Rose 1977), and Fuego Volcano inferred to be less than 10 ka (Chesner and Halsor 1977).

[2] Historical accounts of the eruptions in the 1800’s from Atitlán Volcano come from Sapper (1925).