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Lahar-Hazard Zonation for San Miguel Volcano, El Salvador

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Cover photograph

San Miguel volcano viewed from the south. (*Photograph by J.J. Major, U.S. Geological Survey*).

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By J.J. Major, S.P. Schilling, C.R Pullinger, C.D. Escobar, C.A. Chesner, and M.M. Howell

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Lahar-Hazard Zonation for San Miguel Volcano, El Salvador

By J.J. Major, S.P. Schilling, C.R Pullinger[1], C.D. Escobar[1], C.A. Chesner[2], and M.M. Howell

INTRODUCTION

San Miguel volcano, also known as Chaparrastique, is one of many volcanoes along the volcanic arc in El Salvador (figure 1). The volcano, located in the eastern part of the country, rises to an altitude of about 2130 meters and towers above the communities of San Miguel, El Transito, San Rafael Oriente, and San Jorge. In addition to the larger communities that surround the volcano, several smaller communities and coffee plantations are located on or around the flanks of the volcano, and the PanAmerican and coastal highways cross the lowermost northern and southern flanks of the volcano. The population density around San Miguel volcano coupled with the proximity of major transportation routes increases the risk that even small volcano-related events, like landslides or eruptions, may have significant impact on people and infrastructure.

San Miguel volcano is one of the most active volcanoes in El Salvador; it has erupted at least 29 times since 1699 [1] (numerals in brackets refer to end notes in the report). Historical eruptions of the volcano consisted mainly of relatively quiescent emplacement of lava flows or minor explosions that generated modest **tephra** falls (erupted fragments of microscopic ash to meter sized blocks that are dispersed into the atmosphere and fall to the ground). Little is known, however, about prehistoric eruptions of the volcano. Chemical analyses of prehistoric lava flows and thin tephra falls from San Miguel volcano indicate that the volcano is composed dominantly of **basalt** (rock having silica content <53%), similar to the lava erupted by Hawaiian volcanoes. The chemical composition of eruptive products and the lack of evidence of large cataclysmic eruptions suggests that prehistoric eruptions probably were similar in nature to the historical eruptions. Unlike San Salvador and San Vicente volcanoes, San Miguel volcano does not appear to have had a history of violent explosive eruptions.

Volcanic eruptions are not the only geologic events that present hazards to local communities. Landslides and associated debris flows (watery flows of mud, rock, and debris--also known as a **lahars** when they occur on a volcano) that can occur during periods of no volcanic activity are also of concern. In 1998 at Casita volcano in Nicaragua, extremely heavy rainfall from Hurricane Mitch triggered a landslide that moved down slope and transformed into a rapidly moving debris flow that destroyed two villages and killed more than 2000 people. Torrential rains at San Miguel volcano in 1988, 1994, 1999 and 2000

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triggered debris flows (lahars) on the northwestern slopes of the volcano, and they traveled downslope and damaged the main road that leads to San Jorge. Although modern landslides and lahars at San Miguel thus far have caused only minor loss of property and have been primarily a short-term inconvenience, destructive rainfall- and earthquake-triggered landslides and debris flows on or near San Salvador volcano (figure 1) in September 1982 and January 2001, and at San Vicente volcano in September 2001, demonstrate that such mass movements in El Salvador can also be lethal.

This report describes the hazards of landslides and lahars in general, and discusses potential hazards from future landslides and lahars at San Miguel volcano in particular. The report also shows, in the accompanying lahar-hazard-zonation map, which areas are likely to be at risk from future landslides and lahars at San Miguel. A report by Chesner (2000) focuses on a broader volcanic-hazard assessment of the volcano.

DEBRIS AVALANCHE, LANDSLIDE, AND LAHAR

The slopes of a volcano can become unstable, fail catastrophically, and generate a **landslide**. A large rapidly moving landslide at a volcano is commonly called a **debris avalanche**. Slope instability at volcanoes can be caused by many factors. Large earthquakes, torrential rains, or steam explosions can trigger landslides perhaps as large as 10 million cubic meters or more. Landslides triggered by these mechanisms are usually relatively shallow, up to several tens of meters deep. On the contrary, magma rising upward through a volcano can push aside older volcanic rock and deform and steepen the flanks of a volcano, or warm acidic ground water can circulate through cracks and porous zones deep inside a volcano, alter strong rock to weak slippery clay, and gradually weaken the volcano so that it is susceptible to large debris avalanches. Debris avalanches triggered by these mechanisms can be

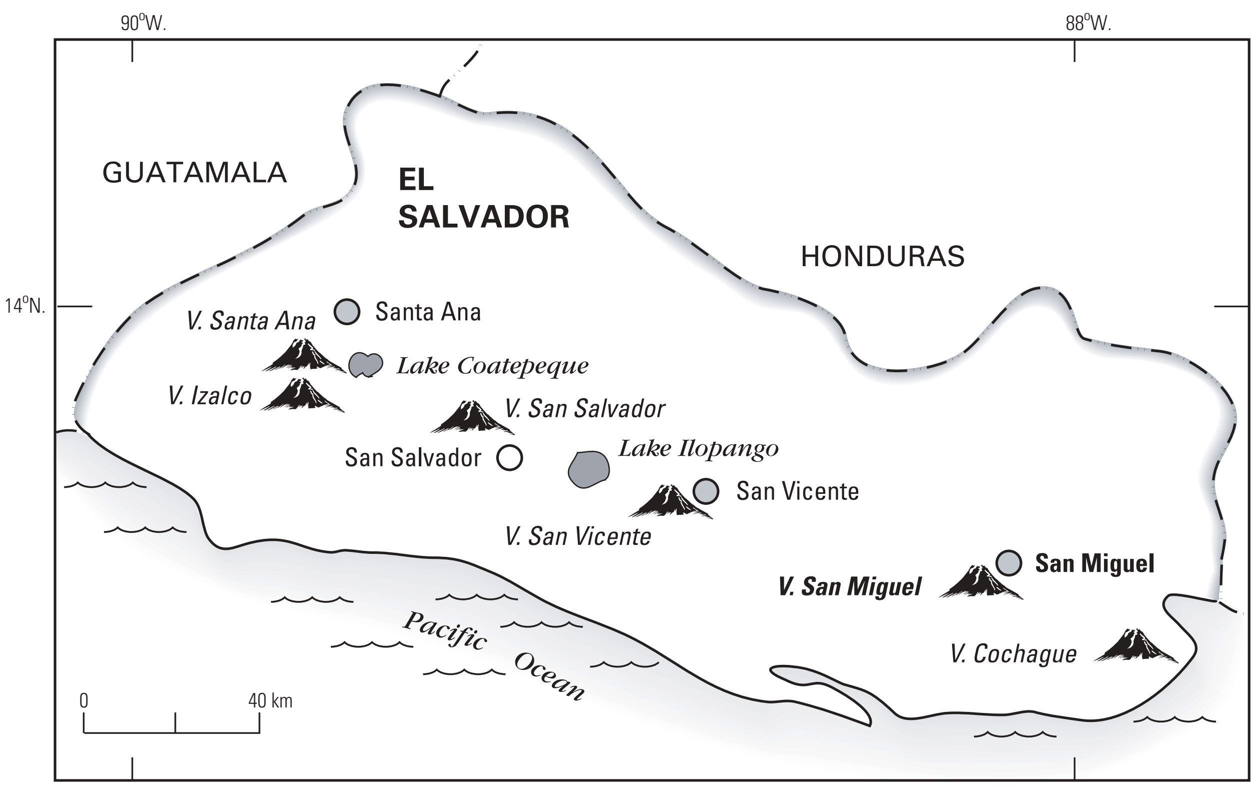

Figure 1. Location of major cities and significant Quaternary volcanoes in El Salvador. Circles indicate major cities, triangles indicate major volcanoes. Lake Coatepeque and Lake Ilopango are large silicic calderas.

on the order of 100 million or more cubic meters in size, and they commonly erode deeply and remove large segments of a volcano. A debris avalanche can attain speeds in excess of 150 kilometers per hour; generally, the larger the avalanche, the faster and farther it can travel. Shallow, small-volume landslides typically travel only a few kilometers from their source, but massive, large-volume debris avalanches can travel tens of kilometers from a volcano. Debris avalanches and smaller landslides destroy everything in their paths and can leave deposits tens of meters thick on valley floors.

Debris-avalanche deposits have been found at numerous volcanoes around the world, including volcanoes in El Salvador. At San Miguel volcano, no deposits of a large debris avalanche have been recognized yet, suggesting that large parts of the volcano have not collapsed catastrophically. Nevertheless, San Miguel volcano is a large, steep-sided volcano, and the possibility of a future large debris avalanche, although slight, cannot be dismissed.

Lahars, also called volcanic mudflows and debris flows, are flowing masses of mud, rock, and water that look much like rapidly flowing concrete. They are produced when water mobilizes large volumes of mud, rock, and volcanic debris. Commonly, landslides and debris avalanches will transform into lahars. Lahars, like floods, inundate floodplains and submerge structures in low-lying areas. They can travel many tens of kilometers at speeds of tens of kilometers per hour. Lahars can destroy or damage everything in their paths through burial or impact. They follow river valleys and leave deposits of muddy sand and gravel that commonly are a few meters thick. They are particularly hazardous because they can travel far distances from a volcano and they affect stream valleys where human settlement is usually greatest. In some instances, lahars can clog a channel or block a tributary channel and impound a lake behind the blockage. Commonly, the impounded water will spill over the blockage and generate a flood that moves down valley endangering people and property.

Like floods, lahars range greatly in size. The smallest lahars recur most frequently (perhaps every few years), whereas the largest typically recur on the order of millennia to tens of millennia. The size of a lahar is controlled by both the amount of water and the amount of loose sediment or volcanic debris available. Large debris avalanches or eruptions can dump tens to hundreds of millions of cubic meters of sediment into channels and produce large lahars. Smaller landslides or eruptions produce smaller lahars.

Landslides and lahars can cause problems long after the event that formed them ends. Once landslides and lahars fill stream channels with sediment, the streams begin to erode new paths, and the new stream channels can be highly unstable and shift rapidly as sediment is eroded and moved farther down valley. Stream shifting can cause rapid and dramatic bank erosion. Furthermore, because stream channels are clogged with sediment, they have less ability to convey water. As a result, relatively small floods, which may have previously passed unnoticed, can pose potentially significant threats to people living in low-lying areas. People living in low-lying areas along river valleys are most susceptible to these secondary affects from landslides and lahars, but areas on higher ground adjacent to river channels may be threatened by bank erosion. Examples from many volcanoes around the world show that the effects of sediment deposition by landslides and lahars in stream channels can persist for years to decades [2].

Landslide and lahar deposits at San Miguel volcano are found only locally. Aside from deposits of rainfall-triggered lahars that occurred within the past twenty years from tephra-covered slopes on the western side of the volcano, a few prehistoric (?) lahar deposits are found on the western flank of the volcano within about 4 km of the summit, and others are exposed locally at the base of the volcano on other flanks. The limited distribution of lahars at San Miguel suggests that eruptions of the volcano have not commonly generated landslides and lahars, nor have extensive lahars formed during noneruptive intervals. More likely, eruptions have blanketed the slopes of the volcano with tephra, and subsequent heavy rains have eroded that sediment or triggered small landslides that have mobilized into lahars.

FUTURE LANDSLIDES AND LAHARS AT SAN MIGUEL VOLCANO

Landslides and lahars, triggered by any of several mechanisms, can occur on any flank of the volcano. The direct effects of most landslides and lahars at San Miguel will likely be confined to within about 10 kilometers of the summit of the volcano, although rare large lahars could travel farther. Such large events, perhaps involving more than about 10 million cubic meters of debris, have a low probability of occurrence and would likely require a substantial tephra-producing eruption or a debris avalanche that removes a large part of the volcano. Both scenarios generally would require magma to rise to a high level in the volcano. When magma rises into a volcano, it is accompanied by increased seismicity, visible deformation of the volcano, and other signs that provide warning of the onset of hazardous conditions.

Future lahars likely will be triggered by erosion or landslides in the tephra mantle that covers the slopes of the volcano, and probably will be smaller than about 1 million cubic meters in size (see discussion in section on lahar-hazard zonation map). Future eruptions of San Miguel likely will produce minor tephra falls that supply sources of new sediment for lahars. In general, the western side of the volcano is more likely to be affected by future lahars owing to tephra distribution. Although prevailing winds are seasonal, easterly winds tend to dominate [3], and tephra thicknesses generally appear to be greater on the western flank of the volcano than on other flanks.

Although the direct effects of landslides and lahars are likely to be confined within 10 kilometers of the volcano, secondary effects related to sediment erosion and transport along channels can affect areas farther from the volcano and can linger for several years. Such secondary effects involve reworking and redistribution of sediment, bank erosion, loss of channel capacity, and enhanced hazards of floods in low-lying areas.

LAHAR-HAZARD-ZONATION MAP

Because the details of the eruptive and landslide history of San Miguel are poorly known, we rely on data from volcanoes around the world that are similar to San Miguel to gain a general idea of the possible hazards from landslides and lahars. This is a reasonable method because similar types of landslides and lahars occur at many volcanoes, even though the exact types that occur, and their relative frequencies and sizes, vary among volcanic centers.

The accompanying lahar-hazard-zonation map (plate 1) shows areas that could be affected by future landslides and lahars at San Miguel. The location and size of an affected area will depend on the location of a landslide or area of substantial flank erosion, the volume and character of sediment involved, the shape of the channel in which the lahar occurs, and whether or not magmatic intrusion was a key triggering process.

Potential areas of lahar inundation along major channels that drain San Miguel volcano are divided into nested zones on the basis of the size of the lahar and their relative degree of hazard. Inundation boundaries are drawn on the basis of mathematical models that use calibrations from other volcanoes to predict the probable extent of lahars, and on our experience and judgement derived from observations and understanding of landslides and lahars at similar volcanoes.

Although we show sharp boundaries for the lahar-hazard zones, the limit of the hazard does not change or end abruptly at these boundaries. Rather, the hazard decreases gradually as distance from the volcano increases, and decreases rapidly with increasing elevation above channel floors. Areas immediately beyond outer hazard zones should not be regarded as hazard-free, because the limits of lahar hazard can be located only approximately, especially in areas of low relief. Many uncertainties about the source, size, and mobility of future lahars preclude locating the boundaries of zero-hazard zones precisely.

Users of the hazard map in this report should be aware that the map does not show all areas subject to hazardous landslides and lahars from San Miguel volcano. For this report, we defined zones of inundation from lahars of various volumes for prominent channels directed toward populous areas. Other channels for which we have not modeled lahar inundation should not be considered as areas devoid of lahar hazard.

We used a mathematical technique calibrated with data from other volcanoes [4] to estimate potential areas of inundation by lahars of various volumes. For each channel analyzed, we define nested hazard zones that depict anticipated inundation by hypothetical "design" lahars having different volumes. We focus on estimating inundation areas of lahars likely to be triggered by earthquakes or torrential rains, as these are the most common causes of lahars at San Miguel volcano. We do not estimate areas of inundation from a large debris avalanche that might be triggered by magmatic intrusion into the volcano. Events of this type, particularly at basaltic volcanoes, are rare. The largest design lahar selected for initiation within a single channel, 1 million cubic meters, reflects our estimate of the largest probable lahar that could be triggered by earthquakes or torrential rains at San Miguel [4]. The intermediate (300,000 to 500,000 cubic meters) and smallest (100,000 cubic meters) design lahars are more typical volumes that might result from landslides triggered by such events. Landslides and lahars of these sizes have occurred historically at San Miguel volcano, as well as at San Salvador and San Vicente volcanoes, and lahars of up to 500,000 cubic meters are the most likely sizes to occur again.

Large lahars are less likely to occur than small lahars. The annual probability of lahars of various sizes is difficult to estimate, because ages and extents of prehistoric lahars at San Miguel are not known. On the basis of examining the probabilities of occurrence of landslides and lahars of various sizes at other major volcanoes within the country [5] it is likely that landslides and lahars of 1 million cubic meters or more in size have an annual probability of occurrence that is less than 1 in 10,000. Smaller landslides and lahars are much more likely to occur; lahars of about 500,000 cubic meters or less may have an annual probability of about 1 in 100 to perhaps as great as 1 in 5 [6]

In general, lahar hazard zones are within about 10 kilometers of the summit crater. Local topography plays a large role in controlling lahar runout. Although landslides and lahars originate in and flow along steeply incised drainages on the flanks of the volcano, these channels shallow and the topography flattens abruptly beyond the base of the edifice. As a result, lahars rapidly spill out of channels, spread, and stop. The most distant hazard zones are associated with the deepest incised channels in which lahars remain confined. Despite their relatively short runout distances, even the smallest lahars can cause fatalities and damage infrastructure Although major communities near the volcano are located 10 kilometers or more from the summit of the volcano, smaller communities, coffee plantations, and important transportation routes are located on the lower flanks of the volcano and lie within 10 kilometers of the summit. The hazard zones of even the smallest lahars extend well into areas that are now settled or used for agriculture.

LAHAR HAZARD FORECASTS AND WARNINGS

It is difficult, if not impossible, to predict the precise occurrence of landslides and lahars triggered by earthquakes or torrential rains. However, generally hazardous conditions that favor formation of landslides and lahars can be recognized. Forecasts for very heavy rainfall, which commonly trigger flood warnings, can serve as indicators of conditions favorable for landslides and lahars. When San Miguel volcano erupts again, it is likely to disperse tephra fall on its flanks. Subsequent erosion of that tephra can generate lahars similar to those that have occurred in past 20 years. In this case, the eruption of the volcano can serve as a warning that conditions are favorable for lahar formation, and the distribution of tephra fall can indicate which flanks are more likely to be affected. In the rare event of a large debris avalanche triggered by intrusion of magma into the volcano, deformation of the volcano will serve as a warning that conditions are hazardous. However, government officials and the public need realize that potentially lethal events can occur in the lahar hazard zones with little or no warning.

PROTECTING COMMUNITIES AND CITIZENS FROM LAHAR HAZARDS

Communities and citizens must plan ahead to mitigate the effects of future landslides and lahars from San Miguel volcano. Long-term mitigation efforts must include using information about lahar and other volcano hazards (see Chesner, 2000) when making decisions about land use and siting of critical facilities and development. Future development should avoid areas judged to have an unacceptably high risk or be planned and designed to reduce the level of risk.

Depending on the distance from the volcano, the hazard zones depicted on the map are areas that will be affected within a few minutes to about one hour after the onset of a lahar. Beyond 10 kilometers from the volcano's summit escape may be possible if people are given sufficient warning. Within 10 kilometers of the volcano lahars may happen too quickly to provide effective warning. Therefore, citizens must learn to recognize for themselves hazardous conditions that favor formation of landslides and lahars.

Because landslides and lahars can occur without warning, suitable emergency plans for dealing with them should be made in advance. Although it is uncertain when landslides and lahars will occur again at San Miguel volcano, public officials need to consider issues such as public education, communications, and evacuations as part of a response plan. Emergency plans already developed for floods may apply to some extent, but may need modifications. For inhabitants in low-lying areas a map showing the shortest route to high ground would be helpful.

Knowledge and advance planning are the most important items for dealing with landslide and lahar hazards. 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 channels that drain San Miguel 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. For areas beyond about 8 kilometers from the summit of the volcano, all but that largest lahars will rise less than about 10 meters above river level. Landslides and lahars from San Miguel volcano will happen again, and the best way to cope with these events is through advance planning in order to mitigate their effects.

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END NOTES

[1] The geologic data upon which this report is based come largely from Williams and Meyer-Abich (1955); Escobar et al. (1993); Simkin and Siebert (1994), Chesner (2000); communications with personnel at Centro de Investigaciones Geotécnicas, San Salvador; and our own reconnaissance investigations.

[2] Analyses of limited data from volcanoes around the world indicate that sediment yields from river channels filled with volcanic debris by an eruption can remain higher than typical background levels for years to decades after an eruption. In some cases sediment yields can remain 10 to 100 times greater than typical background levels for more than two decades (Major et al., 2000).

[3] Upper-level wind patterns in Guatemala between 3000 and 15,000 meters altitude are strongly seasonal (Mercado et al., 1988). Similar wind patterns are likely in El Salvador. From January to March, westerly winds dominate. April and May are transitional months in which westerly winds give way to more northerly and easterly winds. June through October are characterized by easterly winds, and November and December are transitional months during which westerly winds gradually become dominant. The strong seasonality of these winds will influence areas affected by tephra falls. Erupted tephras will likely fall eastward of the volcano from January through March, potentially cover broad regions to the east, south, and west in April and May, affect areas west of the volcano from June through October, and possibly areas west, north, and east of the volcano in November and December. Surface winds may also affect tephra distributions, and their patterns are diurnal as well as seasonal (Portig, 1976). Therefore, all sectors around San Miguel volcano can be affected by tephra fall, but overall the western flank is more likely to be affected owing to the slightly higher probability of easterly winds.

[4] Lahar hazard zones were constructed by modeling lahar volumes of 100,000; 300,000; 500,000; and 1 million cubic meters. Using mathematical and digital cartographic techniques (Iverson et al., 1998), these volumes were used to compute the estimated extent of inundation down stream from a source area. Although undated lahar deposits have been identified at San Miguel volcano and four lahars have descended the flanks of the volcano within the past 13 years, the volumes of these events are poorly known. Regionally, earthquake- and rainfall-triggered landslides and lahars have had volumes as large as 10 million cubic meters, but most have had volumes of a few hundred to a few hundreds of thousands of cubic meters (Rymer and White, 1989; Baum et al., 2001; E.L. Harp and A.J. Crone, U.S. Geological Survey, personal communication). At Casita volcano in Nicaragua, extremely heavy rainfall from Hurricane Mitch triggered a landslide of about 1.5 million cubic meters in

volume, but as it moved down slope it transformed into a lahar that scoured its channel and its volume enlarged to more than 3 million cubic meters (K.M. Scott, U.S. Geological Survey, personal communication). On the basis of these data, we select a landslide and associated lahar of 1 million cubic meters to be a probable maximum size likely to be triggered in any single channel at San Miguel volcano by earthquakes or torrential rainfalls.

[5] Probabilities of occurrence of lahars having volumes of 1 million cubic meters or more at San Salvador and San Vicente volcanoes are given in Major et al. (2001a, b).

[6] We estimate possible annual probabilities of landslides and lahars having volumes of 500,000 cubic meters or less at San Miguel volcano as follows. Historical earthquake-induced landslides have occurred throughout El Salvador at least a dozen times from 1857 to 2001 (Rymer and White, 1989; Baum et al., 2001). Volumes of these landslides have ranged from a few hundred to more than 10 million cubic meters, but most have had volumes of less than a few to a few tens of thousands of cubic meters. Thus, earthquake-induced landslides of small to moderate volume occur in El Salvador about once every 12 years. At San Miguel volcano, known rainfall-triggered landslides and lahars have occurred four times within the past 13 years, which suggest that annual probabilities of occurrence of such events may be as great as 1 in 3. These modern lahars did not reach major communities, but they did damage the main road leading from the PanAmerican highway to San Jorge (see plate 1). The volumes of these lahars are not known, but their extents suggest volumes on the order of 100,000 cubic meters or more. Although the estimated probabilities determined above are highly generalized, we suggest that the annual probability of landslides and lahars ≤500,000 cubic meters in size at San Miguel volcano is about 1 in 100 (comparable to San Salvador volcano; see Major et al., 2001a) to perhaps as great as 1 in 5.

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