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The Editor
Disaster Preparedness in the Americas
Pan American Health Organization
525 23 rd St., N.W.
Washington, D.C. 20037

Dear Editor:

I enclose a copy of a manuscript on "Volcanic disasters in Latin America and the 13th November 1985 eruption of Nevado del Ruiz volcano in Colombia".

The paper is in press in "Disasters", the International Journal of Disaster Studies and Practice, vol. 10, No. 3, 1986. You may wish to include this reference in the "Selected Bibliography" of your Newsletter.

Sincerely,

Haraldur Sigurdsson
Professor of Oceanography

HS:gsc

Enclosure

VOLCANIC DISASTERS IN LATIN AMERICA AND THE 13 NOVEMBER 1985 ERUPTION OF NEVADO DEL RUIZ VOLCANO IN COLOMBIA

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ABSTRACT

Volcanic eruptions in Latin America have claimed about 61,000 lives since 1600 A.D. and the region's volcanoes are responsible for about a quarter of the world's fatalities from this type of hazard. Nearly all loss of life from volcanism in Latin America is due to pyroclastic surges, pyroclastic flows and lahars or volcanic mudflows. Lahars generated during the 13 November, 1985 eruption of Nevado del Ruiz in Colombia claimed 25,000 lives, underscoring the great hazard from lahars, which can be generated from the fifty-six, active, ice-capped Central and South American volcanoes during even very small eruptions. The probability of specific prediction of the timing of such events is currently low, whereas the probability of a general prediction of volcanic eruption is high, giving sufficient time to install telemetered lahar alarm systems, which could largely avoid the loss of life.

INTRODUCTION

Volcanic eruptions are one of Earth's major natural hazards and have claimed 266,000 lives in the past 385 years. During this period, some fatalities have occurred in 5% of all eruptions, and one out of six of the Earth's active volcanoes has caused deaths. Volcanic eruptions are, however, relatively benign, when compared with the hazard of earthquake activity, which has caused about 20 times this number of deaths in the same period. Because of the increasing population density on our planet, volcanic hazards are, however, of growing concern and likely to take a greater toll in the future, unless volcano monitoring efforts and techniques are greatly improved.

Because of its geologic setting, much of Latin America is a region of high volcanic risk. The steady subduction of the Pacific Ocean floor under the western margin of Central and South America has given rise to a chain of volcanoes on the overriding continental plate. Similarly, subduction of Atlantic Ocean floor from the east has given rise to the island volcanoes of the Lesser Antilles chain. This intense interaction of lithospheric plates in Latin America is responsible for the generation of the approximately 270 currently active volcanoes in this region (fig. 1, table 1). The varied activity of Latin American volcanoes produces a spectrum of volcanic hazards, but historically, two volcanic processes have caused nearly all the human casualities in the region: lahars or volcanic mudflows, and pyroclastic surges.

The death toll due to volcanic activity in Central and South America from 1600 to 1982 is estimated as 5,445 (Blong, 1984). In addition, an estimated 2,000 people lost their lives in the El Chichon 1982 eruption in Mexico, and about 25,000 in the recent 1985 Nevado del Ruiz eruption in Colombia. The total death toll through volcanism in Central and South America from 1600 to 1985 is therefore about 32,000. In the Caribbean region, Blong (1984) estimates 30,761 deaths from 1600 to 1982 with most of those occurring during the May 8, 1902 eruption of Mount Pelee on Martinique. The total loss of life in Latin America due to volcanic activity is therefore about 63,000 in this period, or about 24 % of the total documented global fatalities due to volcanic activity. In this paper, we review some of the most recent volcanic disasters in Latin America, with particular reference to the lethal effects of the lahars generated during the 1985 Nevado del Ruiz eruption in Colombia. Prior to the Ruiz eruption the high risk connected with volcanic lahars in Latin America had not been generally appreciated. There are at least 56 glacier or snow-capped volcanoes in Central and South America, many of which are likely to have lahar-producing eruptions in the future (table 2). Due to the limited monitoring of these volcanoes, the probability of predicting future lahar-producing eruptions is rather low. On the other hand, a lahar-alarm system is likely to be highly effective and could save many lives, as the interval between the generation of a lahar at the volcano and its passage through populated regions is likely to be several hours.

TYPES OF VOLCANIC HAZARD

One of the major problems with volcanic hazard assessment is the identification of active volcanoes. Traditionally, volcanoes that have erupted during the historical period are considered active, and those for which there is no record of historic volcanic activity are considered dormant or extinct. This classification is of limited value, as the historical period, i.e., the period for which written records exist, varies from a few hundred to two thousand years, depending on the region. Furthermore, many recent and devastating eruptions have occurred in volcanoes for which there is no previous record of activity, and some of these mountains were not even known to be volcanic in nature. Prior to its devastating 1982 eruption, there was, for example, no historic record of activity in El Chichon volcano in Mexico, but subsequent studies have shown that its previous eruption was 550 years ago (Tilling et al. 1985). A recent compilation of historic volcanic activity shows that of the 21 largest explosive eruptions, 17 of these were the first historic eruptions for each particular volcano (Simkin and Siebert, 1984). Thus, it is certain that many volcanoes have an interval between eruptions that is much longer than the historic period. Volcanic hazard assessment is further complicated by the unheralded birth of new volcanoes. Paricutin volcano emerged in a corn field in Mexico in 1943, and remained active until 1952. The eruption produced $2x10^9$ m^3 of volcanic deposits, resulting in formation of a 410 m high cone. Similar activity in 1759 produced Jorullo volcano in Mexico, and in 1770 the new Izalco volcano was formed in El Salvador, which remained almost continuously active until 1958, when it had attained a height of 900 m.

Volcanic eruptions range in energy release by several orders of magnitude, are of many types, and generate a variety of processes and deposits. An important parameter is the degree of explosivity during the eruption, and two end-member types can be recognized. Eruptions of lava are non-explosive, relatively quiet outpourings of magma or molten rock, which generally represent minimum hazard. At the other extreme are the highly explosive eruptions of gas-rich magmas, which generate high-altitude plinian eruption columns. The periodic collapse of such eruption columns results in formation of hot density currents of volcanic ash, pumice and hot gases, or pyroclastic surges and pyroclastic flows. Although quite common and widespread, lava flows present a relatively minor volcanic hazard to man. They flow generally quite slowly, of the order of only 200 to 400 m/hr, and thus can be easily avoided by people in their path. The material damage due to lava flows is, however, significant, as all buildings, agriculture and other developments that lie in their path are usually totally destroyed.

Highly explosive eruptions eject large quantities of volcanic fragments (tephra) into the atmosphere as a result of the rapid expansion of gases. Fallout of this material can pose a significant hazard for populations due to roof collapse, danger from the impact of large projectiles and ignition of fires by incandescent pyroclastic fragments over 10 km distance from the vent. Extreme darkness during tephra falls also creates dangerous situations. In general, however, the volcanic hazard from tephra falls is relatively minor and rather localized, whereas the beneficial aspects of tephra fall to agriculture are considerable. Tephra fallout from several Latin American volcanoes has been very extensive. For example, Quizapu (Cerro Azul) in Chile erupted in 1932, resulting in 1/2 cm ash fall in Buenos Aires, Argentina after 17 hrs of transport (1120 km), and five days later the ash fall reached Rio de Janeiro in Brazil, some 2960 km distant. Similarly, the great 1835 plinian eruption of Cosiguina volcano in Nicaragua was sustained for three days, and caused ash fall in Jamaica, 1300 km to the east. This eruption produced a major stratospheric aerosol layer, which backscattered and absorbed a significant fraction of incoming solar radiation and caused Northern Hemisphere surface cooling for two or three years following the eruption. The surface temperatures in Europe were, on the average, 1°C lower in the five years following the event (Angell and Korshover, 1985).

The hazard of tephra accumulation on roofs was demonstrated during the 1902 Santa Maria eruption in Guatemala, where a 20 cm tephra layer was sufficient to cause collapse of most roofs, causing 2,000 deaths (Coleman, 1946). During the 1982 eruptions of El Chichon in Mexico, the roof collapse caused by the first of the three major eruptions proved to be a blessing in disguise, as it forced the voluntary evacuation of a large part of the population within the hazard zone, that was totally devastated five days later by deadly pyroclastic surges (Sigurdsson et al. 1984).

Tephra fall can also contain adsorbed components, such as fluorine, which may be toxic if ingested by livestock. Thus several thousand cattle died from eating ash-covered vegetation during the 1943 eruption of Paricutin in Mexico. Masaya volcano emitted large volumes of sulfur, particularly in 1946, when sulfur fumes damaged 130 km^2 of coffee crops, and killed an estimated 6×10^6 coffee trees. Corrosion of metals by the sulfuric acid aerosol was also a serious problem.

In contrast to the rather benign effects of tephra fall, pyroclastic flows and surges are generally the most hazardous of volcanic phenomena. These density currents of hot gases and particles flow down the slopes of a volcano at speeds of tens to hundreds of meters per second and cover areas of hundreds to a thousand km^2. Because of their sudden generation and high velocity, pyroclastic flows and surges are very difficult to escape and can engulf towns and villages within minutes of their initiation. People in their path are generally asphyxiated in the hot, oxygen-poor and dust-laden cloud, or killed by projectiles or skin burns and buried in the resulting volcanic deposit. Pyroclastic flows generally follow valleys and depressions and their course is, therefore, somewhat predictable. They are extremely hazardous however, and during the 1968 eruption of Arenal volcano in Costa Rica, for example, pyroclastic flows destroyed two villages and killed 78 persons, and during the 1929 eruption of Santa Maria in Guatemala, 23 people were killed by pyroclastic flows.

Pyroclastic surges, on the other hand, have greater mobility and generally spread radially across the terrain around a volcano. During the April 4, 1982 eruption of El Chichon in Mexico a pyroclastic surge was generated at the onset of the event which destroyed nine villages and killed approximately 2,000 people (fig.2). Ironically many of the victims had just returned to their homes after having fled the area a week earlier, when tephra fallout from the April 28 eruption led to roof collapse. The most notorious catastrophe connected with pyroclastic surges, however, was the May 8, 1902 eruption of Mount Pelee on the island of Martinique in the Lesser Antilles. The volcano showed signs of renewed activity several weeks prior to the paroxsymal May 8 event and despite numerous minor explosions which led to tephra fall, the largest city at the base of Mount Pelee, St. Pierre, was not evacuated. On the morning of May 8 a vertical eruption column emerged from the Etang Sec crater and quickly collapsed, forming a nuee ardente (glowing avalanche) which travelled down the Riviere Blanche. The upper, turbulent parts of the nuee ardente expanded and overflowed the confinement of the Riviere Blanche an ash cloud surge (Fisher et al., 1980; Fisher and Heiken, 1982). Within minutes of the beginning of the event, the surge had reached and destroyed the city of St. Pierre (fig. 3). Of the estimated 30,000 inhabitants, only 2 to 3 are known to have survivied. The death and destruction were the result of a combination of intense heat, perhaps as high as 600^{o} C, and hurricane force gas velocities which blew down masonry walls and easily twisted large bars of steel.

An important result of recent studies of pyroclastic surges associated with the eruption of El Chichon and Mount Pelee is that despite the catastrophic results of the phenomena, surges leave only minor traces of their presence in the form of deposits. For example, in the town of Naranjo (fig. 2) 8 km from the summit of El Chichon, only 3 cm of tephra was laid down by the surge which killed all of the inhabitants, blew down a majority of the buildings and set fire to most of the dry wood in the area (Sigurdsson et al. 1984). These observations have important implications for the creation of volcanic hazards maps, which are based on the extent of particular deposit types surrounding a volcano. Because surge deposits can be thin and perhaps easily eroded at their distal limits, the boundaries of risk ascribed to pyroclastic surges may often be underestimated. Careful documentation of the nature of these distal surge deposits and development of field criteria for their reconition in the geologic record of a volcano's acitivity are imperative for the most accurate designation of high risk areas. Surges and pyroclastic flows rarely present a hazard beyond about 20 km radius from the volcano, but within that area, total devastation of life and property can be expected.

The historic record shows that tsunami, or volcano-generated tidal flood waves, are the second most important direct cause of death in eruptions world-wide, after pyroclastic surges and pyroclastic flows. Tsunami are sea waves, which are generated by disturbances of the ocean floor, but may also be related to eruption of very large mass of material into the ocean around a volcano or due to the collapse of the volcanic edifice into the magma chamber. The explosive 1883 Krakatau eruption in the Sunda Straits in Indonesia generated the largest known volcanic tsunami (Simkin and Fiske, 1984). The tsunami was 15 to 40 m in height at a distance up to 50 km from the volcano, and flooded the adjacent coasts up to 5 km inland, with the resulting loss of 36,000 lives. Eruptions that generate tsunami of this magnitude are fortunately rare and restricted to island volcanoes, or volcanoes near the shoreline. Volcanoes in Central and South America are generally located far from the coast line and unlikely to generate tsunami. The Caribbean volcanoes of the Lesser Antilles island arc may, on the other hand, experience tsunami-generating eruptions, although no loss of life is known in the region from this type of activity in the historical period. Tsunami from the frequently active submarine volcano Kick'em Jenny, north of the island of Grenada, should be considered a potential hazard (Sigurdsson and Shepherd, 1974).

Lahars or mudflows from volcanoes have also been responsible for a large number of deaths, either during or following volcanic eruptions. It is estimated that lahars account for at least 10% of all volcano-related fatalities. Lahars are flowing masses of volcanic debris and other sediment intimately mixed with water. The water may be derived from crater lakes, melting of the ice cap of high-altitude volcanoes, or it may originate from heavy rainfall, which often accompanies volcanic eruptions. The sediment in lahars may be derived from primary volcanic debris erupted during the lahar-producing eruption, or it may represent loose sediment and soils eroded during passage of the torrential flood. The Irazu (Costa Rica) eruption of 1963 to 1965 produced secondary lahars, as intense rain storms re-mobilized tephra fall deposits on the volcano. The resulting secondary lahars had velocities up to 36 km/hr., and were locally up to 12 m deep. Over 30 persons were killed in these lahars, and 300 homes were lost.

Cotopaxi in Ecuador is one of the highest active volcanoes on earth (5897 m), and covered by an extensive ice cap above the 4600 m snow line. It has had about 25 lahar-producing eruptions, with some travelling at 27 km/hr and reaching up to 300 km from source. The Cotopaxi eruption of June 1877, which was preceeded by months of phreatic activity, is an example of the continuing hazard of this volcano. On 25 June an explosion occurred, followed by a larger explosion on 26 June, which produced incandescent pyroclastic flows over the crater rim, that caused extensive melting of snow and ice. The floods of water cascaded down the volcano's slopes, and travelled along valleys up to 240 km from the volcano. Loss of life in the flooded villages was about 1,000 people. This style of activity and lahar-generation was thus very similar to the disastrous lahars generated during the 1985 eruption of Ruiz in Colombia, as discussed later.

PREDICTION OF VOLCANIC ERUPTIONS

The current rapid growth in population density in Latin America is accompanied by increased volcanic risk, i.e., the increased probability of loss of life and property due to volcanic eruptions. There is therefore a growing awareness for the need of volcanic hazard assessment and ultimately the prediction of volcanic eruptions. Volcanic hazard at a given volcano is a function of the probability of occurrence and the intensity of a volcanic eruption. A general predicition can be made on the basis of a hazard assessment, that takes into account the eruptive history of the volcano, and thus requires detailed geological studies of deposits from past eruptions and historic activity. Such general predictions can be considered as long-range forecasts, but they are of only limited value, as the fundamental assumption, that past activity is the key to future activity, may not always be valid. Volcanoes are dynamic, growing and changing geophysical systems, that do not necessarily follow a regular pattern of behavior. General predictions, based on previous activity, are thus primarily useful in forecasting the kinds, scales and likelihoods of activity at a specific volcano, but of little value in predicting the timing of future activity. Furthermore, the data base required to carry out a volcanic hazard assessment and a general prediction is unfortunately only available for a handful of volcanoes in Latin America. The greatest hazard may in fact stem from those volcanoes, that are as yet unknown and have not erupted in the historical period, or from volcanoes that are yet to be born.

Another approach to volcanic hazard assessment involves the specific prediction of volcanic eruption, based on geophysical and geochemical volcano monitoring techniques. This approach relies on the detection of precursory events, and utilizes the rate of change in precursory phenomena as a basis for predicting an eruption. Eruption predictions that are based on volcano monitoring rely on the fact that eruptions are preceded by the ascent of magma within the crust, which in turn gives rise to a variety of detectable precursor phenomena. Studies of this sort require, however, extensive instrumentation of the volcano and continuous monitoring to establish baseline information. Because of the costs involved, only a dozen of the Earth's volcanoes are well monitored today, and consequently, specific prediction of an eruption is only feasible for these volcanoes (e.g. Swanson et al., 1983).

As magma moves within the crust, it leads to deformation of the overlying ground surface. Thus, ground deformation studies have become one of the most reliable volcano monitoring techniques and form a basis for short-term prediction. The change in shape of a volcano is monitored by repeated trilateration and triangulation, long-ranging distance measurements between benchmarks on the volcano and in the surrounding terrain, and measurements of ground tilt on the flanks of the volcano. Changes in shape can be quite dramatic, as, for example, in the case of Mount St. Helens before the 1980 eruption, when a bulge on the north flank grew by as much as 2.5 m/day, due to intrusion of magma at a high level within the volcano (Lipman et al., 1981). Renewed volcanic activity is often preceded by influx of magma into a magma chamber, resulting in inflation of the overlying volcano edifice. The inflation is often radial and centered over the reservoir, with ground uplift of the order 1 to 10 mm/day. Such inflation episodes preceded the 1975 to 1984 eruptions of Krafla (Iceland), and similar recent ground inflation in the calderas of Rabaul (Papua-New Guinea) and Campi Flegrei (Italy) led to the issue of volcano alerts, but the level of activity subsided without an eruption.

One of the most useful sources of data for volcanic predictions is seismic monitoring. Earthquakes are generated by a number of mechanisms within the volcanic system preceeding an eruption, such as during fracturing of the crust surrounding an inflating magma reservoir or due to thermal stresses in the crust. Volcanic earthquakes are often seen to increase in numbers several weeks or days before an eruption. The sudden increase in seismic-energy release (strain release) is thus a valuable basis for short-term prediction. Changes in heat flow from a volcano and changes in the composition and emission rate of volcanic gases can be useful in anticipating an eruption. However, these monitoring techniques are less reliable than seismic and deformation studies, due to the relatively slow diffusion rates of heat and gases through the Earth's crust, compared to the near-instantaneous transmission of seismic waves. Geophysical and geochemical monitoring techniques may thus reveal trends in behaviour of a volcano, including a rapid change in some parameters prior to an eruption. While such trends may clearly indicate the increasing likelihood of an eruption, there is generally insufficient historical data base and experience to make a specific prediction on the basis of such trends. Because of the poor monitoring of most volcanoes, and because of the relative infancy of the art of volcano eruption prediction, there is a clear need for implementation and maintenance of simple alarm systems, which are activated automatically once an eruption begins. Such systems could, for example, have saved thousands of lives in the 1985 volcanic disaster in Colombia.

NEVADO DEL RUIZ 1985 ERUPTION

Lahars generated by the eruption of Nevado del Ruiz volcano in Colombia on 13 November 1985 caused the death of an estimated 25,000 people in several towns at the base of the volcano. It is the largest volcanic disaster since the tragic 1902 eruption of Mount Pelee in Martinique, when at least 28,000 people were killed by hot pyroclastic surges and flows. In both of these eruptions the mass of erupted magma was relatively small, but the large loss of life was due to the unfortunate location of large population centers directly in the pathways of density currents of primary and secondary volcanic debris. Prior to the Ruiz eruption, the largest known number of deaths due to lahars occurred at two Indonesian volcanoes: in the 1919 Kelut eruption, where 5,110 people died, and in the 1822 eruption of Galunggung, with 3,600 casualities. The hazard from lahars at Ruiz volcano was well known in 1985, and shortly before the 13 November eruption, scientists of INGEOMINAS (Instituto Nacional de Investigaciones Geologico-Mineras) and Universidad de Caldas issued a volcanic hazard map, which accurately delineated the areas, which were affected by the lethal lahars a few days later.

Nevado del Ruiz volcano is located in the central cordillera of Colombia, in the northern part of the Andean volcanic chain and had previously erupted in 1595, 1828-29, 1832-33 and 1845 (Simkin et al. 1981, Herd et al. 1986). The 5,389 m high volcano consists of a broad and relatively flat lying shield of andesitic and basaltic lavas, capped by a 17 km^2 glacier, with an average thickness of only 20 m (J.C. Thouret, pers. comm.). Previous historic and prehistoric eruptions at Ruiz had generated lahars with sometimes catastrophic results. During the 1845 eruption, for example, lahars from the Azufrado and Lagunillas rivers discharged over the present site of Armero (Acosta, 1846) and a lahar in the Recio river is reported to have destroyed the town of Ambalema, with 1000 casualities. The following 140-year period of dormancy was characterized by steady fumarolic activity from the Arenas crater near the northern rim of the ice sheet. In November 1984 the first precursors of the current activity were a series of earthquakes up to magnitude 4, felt on the upper flanks of the volcano (SEAN Bull. 10, 9, 1985). This led to the installation of a seismic monitoring network in July 1985, which recorded earthquakes under the volcano at a rate of 17/day from July to October, 1985. On 11 September, 1985, a small phreatic explosion occurred, which caused minor ash fall over the towns of Manizales and Chinchina, 30 and 35 km west and north-west of the volcano, respectively (Fig. 1). This activity also triggered a small lahar on the north flank of the volcano, which travelled a distance of 27 km down the Azufrado river, but caused no damage.

The 13 November (all times local) eruptive sequence began with a small explosion in the Arenas crater at 3 pm, which caused minor ash fall in the northern towns of Fresno and Mariquita at about 4 pm, and Honda about 5 pm (Fig. 4). At 9:09 pm on the same day, the main explosive eruption began, producing a Plinian eruption column, which was sustained for about 20 minutes, but punctuated by two explosions. Fall of tephra from this phase began at about 9:30 pm in villages 20 km north and northeast of the volcano and was most intense about 10 pm, but ceased shortly after midnight in most areas. Most of the fallout occurred over an area to the north-east of the volcano and can be traced up to 80 km from source (Fig. 4). The dispersal of tephra was, however, much more extensive during the eruption, and minor ash fall was reported up to 400 km NE of the volcano. The maximum thickness measured along a traverse 5 km downwind of source was 7 cm. Some coarse pumices fell sufficiently hot to scorch vegetation and started small grass fires within 5 km of the crater.

The eruption column reached an altitude of 31 km above sea level during the climax of the eruption and some tephra injection into the stratosphere may therefore have occurred (Naranjo et al., 1986). It is likely, however, that the north-easterly tephra dispersal was controlled mainly by upper tropospheric winds. The Ruiz eruption column was higher than the average May 1980 Mount St. Helens column, but because the duration of the Ruiz event was less than one tenth of the Mount St. Helens eruption, the resulting fall deposit was correspondingly smaller. The volume of tephra is 3.9×10^7 m^3, and the total mass of the fall deposit is only 3.5×10^{10} kg (Naranjo et al. 1986).

The eruption also generated minor pyroclastic surges and flows, which were of primary importance in generating the devastating floods, but the details of the timing, distribution and origin of pyroclastic flows and surges are poorly known. A pyroclastic surge, that had travelled about 2 km across the glacier, destroyed a ski lodge on the west slope of Ruiz at about 4,800 m elevation. Part of the roof, wall partitions and furniture were scattered downslope from the building to the west. The surge left a cross-bedded tephra deposit against the walls of the building, which was still warm a few days after the eruption. In the Azufrado valley, ca. 1 km north-northeast of the crater, the eruption deposited a small (0.6 m) pyroclastic flow, that is overlain by a 0.7 m surge deposit, 0.12 m of tephra fall, and a 1.0 m lahar deposit, capped by a minor fall deposit. Minor pyroclastic flow and surge activity therefore occurred at the onset of the eruption, and preceeded the tephra fall.

Although the eruption of Nevado del Ruiz was a small sub-Plinian event, it was associated with highly destructive and lethal lahars that formed by extensive melting of the volcano's glacier cover. Studies of the recent deposits on the upper flanks of the volcano show that these phenomena were initially water-dominated floods, which issued from the surface of the glacier, and gradually transformed into lahars as they incorporated sediment along their course. Three major lahars issued onto the lowlands surrounding Ruiz volcano, after a drop in elevation of about 4 km (Fig. 5). In the headwaters of the Guali river, on the north flank of Ruiz, a lahar was generated after the initial tephra fall and reached the outskirts of Mariquita at 11:30 pm on November 13, and later passed the town of Honda at 2 am the following morning, after 90 km of flow (Fig. 5). A short distance upstream from Mariquita, the Guali lahar was up to 8 m thick when active, and 250 m wide. Because of its high fluidity, the lahar ran out and left a relatively thin deposit, which ranges from 1 m in center of the flow channel to 0.5 m at the margins. When active, the lahar apparently transported boulders several meters in diameter which are now stranded in the center of the river bed. A minimum velocity of flow of 28 km/hr. can be calculated for this lahar, from source to Mariquita, assuming that it was initiated at the time of the explosive eruption. During flow from Mariquita to Honda, however, the Guali lahar slowed down to 9 km/hr, and deposited much of its load as a 1 to 2 m thick layer as it flowed over a gentler slope. It was still highly destructive in Honda where it rose 5 m above the normal level of the Guali river, destroying over 20 houses and claiming at least two lives.

The largest lahar of the eruption was formed by a combination of meltwater floods from the headwaters of the Lagunillas and Azufrado rivers, which dissect the east and northeast flanks of the volcano (Fig. 5). After travelling roughly 70 km, the lahar inundated the town of Armero at about 11 pm, killing most of the population of 25,000. Reports of survivors indicate that it struck in two or three waves. There were also descriptions of scalding hot water in the lahar, although these have not been confirmed and there were no indications of thermal burns on any of the victims. As the lahar emerged from the confinement of the Lagunillas valley , a short distance above the town of Armero, it branched into three lobes (fig. 5). One lobe flowed north, towards the town of Guayabal, the main lobe continued east through Armero, and the smallest lobe flowed south-east along the Lagunillas river bed. The deposit of the distal lobes is yellowish-brown, fine-grained, and rarely more than 0.5 m thick and typically has scalloped edges. In the vicinity of Armero, however, the deposit thickens to 3 to 4 m and is markedly coarser-grained, with large boulders along the center of flow. Many of the buildings in Armeo were sheared off at their foundations, attesting to the enormous momentum of the flow (fig.6).

The lahar which destroyed Armero was a complex event, and its character was probably affected by the presence of a small lake, which had recently formed behind a landslide dam in the lower part of the Lagunillas river, above Armero. Deposits left by the lahar show evidence of different pulses, as suggested by the eyewitness accounts. The distal part of the lahar deposit, e.g. near Guayabal, is thinner, buff to yellowish-brown and appears to have been a more dilute flow, whereas the main part covering the town of Armero is a dark gray, coarser-grained and thicker deposit. It is possible that the first lahar pulse to strike Armero was derived initially from the Lagunillas valley, 60 km from Armero. Bursting of the natural dam in the Lagunillas river may have contributed to the intensity of this lahar. Although probably generated at the same time, the Azufrado lahar had a greater distance of flow (70 km) and probably reached Armero shortly after the Lagunillas lahar. In the headwaters of the Azufrado the lahar deposit is over- and underlain by tephra fall indicating that it was initiated at about 9:10 pm. This would give an average velocity of 38 km/s based on its arrival at Armeo around 11 pm.

On the west flank of Ruiz, a lahar flowed down the headwaters of the Molinos river and into the Chinchina river (fig. 5). At about 10:30 pm, it flooded low-lying parts of the town of Chinchina , claiming about 1,000 lives and causing damage to buildings and roads. The lahar continued the length of the Chinchina river and was eventually discharged into the larger Cauca river, after more than 60 km of flow. Overbank deposits from this flow on upper flanks of the volcano consist of eroded soil and other surface sediments, mixed with juvenile tephra fall. Thus the Chinchina lahar was initiated during deposition of the tephra fall layer on the volcano. The minimum velocity of the Chinchina lahar is estimated as 22 km/hr.

A common analogy used in the description of lahar movement and texture is that it resembles the flow of wet concrete. Several features indicate, however, that the Ruiz flows were much more water-rich and turbulent at the time of flow. Splash marks on walls, many meters above the flow level in Chinchina and Honda indicate jets and fountaining from a dilute flow as it encountered obstacles (fig. 7). The lahars were sufficiently dilute and fluid to maintain flow on very low slopes in meandering river channels, without significant deposition. In addition, extensive drainage channels beyond the ends of the distal flow lobes indicate large-scale dewatering after deposition. Furthermore, the sedimentary features of the deposit indicate deposition from hyperconcentrated flood flow and thus original solid contents probably ranged from 35 to 65 vol.%. The total volume of the lahar deposits was 3 to 6×10^7 m^3 and thus the amount of water in the lahars was 1 to 6×10^7 m^3.

The principal source of water for the Ruiz lahars lies in the summit glacier of the volcano, with an estimated volume of 3×10^8 m^3 prior to eruption (Fig. 8). The contribution of normal river runoff to the lahars must have been minor based on normal discharges. These figures suggest that the recent activity led to melting of 5 to 15% of the volume of the glacier. The evidence for high fluidity in the Ruiz lahars suggests a high ratio of water to sediment. Factors which contributed to this condition include a relatively small volume of new pyroclastic material ejected during the eruption and a large volume of water derived by melting of glacial ice. Indeed, most of the sediment in the lahars was soil eroded from the river valleys, whereas the amount of primary eruptive material was minor. The lahars were thus initiated in the headwaters of the rivers as sediment-starved floods that increased their sediment load at lower elevations by erosion. Mass balance calculations indicate that the sediment contained in the lahar deposits could be accounted for by the erosion of 1 to 2 m of material from the stream valleys on the flanks of the volcano.

Generation of meltwater to initiate the deadly lahars at Ruiz probably occurred by several processes, including glacial surface melting by hot tephra fall, pyroclastic flows and surges, sub-glacial melting by geothermal activity, and melting in glacier avalanches during break-up of hanging valley glaciers. The fronts of the steep hanging glaciers in the headwaters of the Azufrado and Lagunillas rivers were removed during the eruption, representing approximately 2% of the ice sheet. It is likely that these glaciers surged and broke up during the eruption, and contributed to the Azufrado and Lagunillas floods. No blocks of ice were observed, however, in the lahar deposits, unlike in the 1845 eruption, when ice from the glacier was carried by lahar to the Magdalena river. Melting due to tephra fall on ice must be considered as minor, because of the small volume of tephra fall and the limited surface area of the glacier (17 km^2). For example, if the glacier was covered by a 0.5 m thick, coarse grained fall deposit, with clasts initially at 400° C, and half of the thermal energy was utilized to melt ice, only about 10% of the water could be accounted for by this process. Melting of glacial ice by the passage of pyroclastic surges and pyroclastic flows is potentially a more efficient mechanism for generating large volumes of water (Fig. 8). Lahar generation by gravity currents of steam and pyroclasts has been observed, for example, during the 1947 Plinian eruption of Hekla in Iceland (Kjartansson, 1951) and the May 18, 1980 eruption of Mount St. Helens (Pierson, 1985). Thus, thermal and mechanical erosion of the glacier by pyroclastic surges and flows may have been the dominant process for generating meltwater and triggering the catastrophic lahars. It is also possible, however, that subglacial melting by the geothermal system had built up localized reservoirs of meltwater at the base of the glacier or in tunnels and crevasses near the summit crater, that were catastrophically released during the eruption. Such discharges are common in Iceland where they are known as jokulhaup (Bjornsson, 1975). Although there is no direct evidence as yet for jokulhaup-like discharges at Ruiz, all of the conditions necessary for such activity were present.

The social and economic effects of the Ruiz eruption were immense. The lahars affected a 1000 km^2 area, and seriously disrupted the agricultural economy of this region. More than 5,200 persons required immediate emergency medical attention and 1,200 required hospitalization. Nearly 200 km of roads were destroyed; more than 100 kt of agricultural products were lost and 129 km^2 of agricultural land damaged or destroyed; 12,000 head of cattle were lost. Total loss of property is estimated as $US 300 million (Rivera, 1986; Herd et al. 1986). The loss of 25,000 lives and the many injuries could, of course, have been prevented by a prediction of the eruption, but the available evidence from the limited monitoring effort does not indicate any clear trends, that might have formed a basis for a specific prediction of the timing of the eruption. Ruiz sent out a number of signals prior to the eruption, beginning with felt and recorded earthquakes in the summit region and increased fumarolic activity in November 1984, phreatic explosions in August and September 1985, and intermittent volcanic tremor from August 1985 and onward. Seismic monitoring began in July 1985, and the records show no apparent tremor precursors to the 13 November eruption. Unfortunately, there were no deformation studies of the volcano before the event, and the monitoring potential of this parameter is therefore unknown. Gases in fumaroles in and around the crater showed decrease in the ratios S/CO_2 and HCl/H_2S before the eruption, probably due to increase in magmatic gases relative to meteoric water vapor, but it is not clear that these trends could have formed a basis for a specific prediction of the eruption.

A general eruption forcast, however, had in effect been made by Colombian scientists who issued a volcanic hazard map and report on October 7, 1985. The report stressed the hazard from lahars and accurately specified the areas of highest risk, including the ill-fated towns of Armeo and Chinchina. As the data base for a specific prediction of the exact timing of an eruption did not exist, no evacuation of even the most vulnerable areas was enforced. In this type of situation, scientists and authorities are faced with an almost impossible decision, whether to play it safe, and evacuate a region for an unknown period of time, resulting in potentially enormous economic loss and great social displacement, or to wait until even more threatening signs of an imminent eruption make evacuation a more obvious choice. The classic case of this quandry occurred during the controversial volcanic crisis in Guadeloupe in the Lesser Antilles in 1976, when 73,000 people were evacuated from the region of volcanic hazard for 3.5 months, resulting in huge economic consequences and great social strain (Blong, 1984). In Guadeloupe, however, only minor phreatic explosions followed, and no magmatic eruption occurred.

In retrospect, the wisest course of action in the Ruiz crisis, before the 13 November 1985 eruption, would have been the installation of a lahar-alarm system, which could have saved most or all lives. The lahars flowed a distance of 50 to 90 km from their source, before reaching densely populated areas two or three hours later. A system of very simple and inexpensive flood monitors, such as Japanese scientists have now installed in the headwaters of major rivers on the volcano, could have sent early warning of the floods by telemetry, to the populated areas and given sufficient warning for evacuation. The installation of such a simple alarm system is the first logical step, when a lahar-producing volcano shows signs of awakening, and a general predicition of eruption can be made. The population is then no longer at the mercy of the uncertain specific prediction, but can place confidence in the pragmatic and practical alarm system. It is to be hoped, that the tragedy of Armero will now stimulate authorities in Colombia and elsewhere in Latin America to carry out volcanic hazard assessment of the many ice-capped volcanoes, and develop the civil defense infrastructure necessary to deal with such future volcanic diasters. There are fifty six volcanoes in Central and South America, that have a high probability of producing volcanic lahars due to large-scale melting of snow and ice during future eruptions (Table 2). These volcanoes are all regarded active (Simkin et al, 1981), and have substantial ice caps. They include two volcanoes in Mexico, four in Colombia, four in Ecuador, six in Peru, and no less than forty snow-covered and active volcanoes in Chile. Many of these volcanoes are located in remote areas and therefore represent minor volcanic risk, while others have run-off systems into densely populated areas and constitute an important volcanic hazard.

REFERENCES

Acosta, *J. Compt. Rend. de l'Acad. des Sciences*, Paris, **T.22**, p. 709-710, 1846.

Angell, J.K., and J. Korshover. *J. Climate and Appl. Meteorol.*, v. **24**, p. 937-951, 1985.

Blong, R.J. Volcanic hazards, a sourcebook on the effects of eruptions. Academic Press, 424 pp., 1984.

Bjornsson, H. Subglacial water reservoirs, Jokulhlaups and volcanic eruptions.*Jokull*, v. **25**, p. 1-14, 1975.

Coleman, S. N. Volcanoes, new and old. John Day, New York, 1946.

Fisher, R. V., Smith, A. L. and M. J. Roobol. Destruction of St. Pierre, Martinique, by ash-cloud surges, May and 20, 1902. *Geology*, v. **8**, p. 472-476, 1980.

Fisher, R. V. and G. Heiken. Mt. Pelee, Martinique: May 8 and 20, 1902, pyroclastic flows and surges. *J. Volc. Geotherm. Res.*, v. **13**, p. 339-371, 1982.

Herd, D. and Comite de Estudios Vulcanologicos. The 1985 Ruiz volcano disaster. *EOS*, v.**67**, p.457-460.

Kjartansson, G. Water flood and mudflows. In: Einarsson, T., Kjartansson, G. and Thorarinsson, S. eds. The eruption of Hekla, 1947-1948. Visindafelag Islendinga, Reykjavik, p. 1-51, 1951.

Lipman, P., Moore, J. G., and D. Swanson. Bulging of the north flank before the May 18 eruption-geodetic data. *U.S. Geol. Surv. Prof. Paper*, **1250**, p. 143-156, 1981.

Morris, L., T. Simkin and H. Meyers. Map of the volcanoes of the world. The World Data Center A, for Solid Earth Geophysics.

Naranjo, J., Sigurdsson, H., Carey, S., and W. Fritz. The November 13, 1985 eruption of Nevado del Ruiz volcano, Colombia: Tephra fall and lahars. *Science*, (in press), 1986.

Pierson, T. C. Initiation and flow behaviour of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington. *Geol.Amer.Soc.Bull.*, vol. **96**, p. 1056-1069, 1985.

Rivera, A. Events leading to Colombia's Ruiz volcano eruption and its results described. *Min. Eng*. February, p. 99-100, 1986.

SEAN Bulletin. Nevado del Ruiz eruption. v. **10**, nos.9 and 11, 1985.

Sigurdsson, H. and J. Shepherd. Amphibole-bearing basalts from the submarine volcano

Kick'em Jenny in the Lesser Antilles Island arc. *Bull. Volc.*, v. **38**, p.4, 1974.

Sigurdsson, H., Carey, S. and J.M. Espindola. The 1982 eruptions of El Chichon volcano, Mexico: stratigraphy of pyroclastic deposits. *J. Volcanol. Geotherm. Res.*, v. **23**, p. 11-37, 1984.

Simkin, T., Siebert, L., McClelland, Bridge, D., Newhall, C., and J. Latter. Volcanoes of the World. Hutchinson Ross Pub. Co., Stroudsburg, Penn., pp.232, 1981.

Simkin, T. and R. Fiske. Krakatau 1883 The volcanic eruption and its effects. Smithsonian Institution Press, Washington, D.C., p. 464, 1983.

Simkin, T. and L. Siebert. Explosive eruptons in space and time: durations, intervals, and a comparison of the world's active volcanic belts. In: Explosive Volcanism: Inception, Evolution, and Harzards. National Academy Press, Washington, D.C., p. 110-121, 1984.

Swanson, D., Casadevall, T., Dzurisin, D., Malone, S., Newhall, C., and C. Weaver. Predicting eruptions at Mount St. Helens, June 1980 through December 1982. *Science*, v. **221**, p. 1369-1376, 1983.

Tilling, R., Rubin, M., Sigurdsson, H., Carey, S., Duffield, W., and W. Rose. Holocene eruptive activity of El Chichon volcano, Chiapas, Mexico. *Science*, v. **224**, p. 747-749, 1984.

Table 1. Active Volcanoes in Latin America*

Mexico	35
Guatemala	25
El Salvador	20
Nicaragua	22
Costa Rica	11
Honduras	2
Panama	1
Colombia	13
Ecuador	11 plus 16 in Galapagos,
Peru	10
Bolivia	15
Chile	79
Argentina	3
West Indies	18 (Simkin et al., 1981) 23 (J.B. Shepherd, pers. comm.)

* Simkin et al. 1981

Table 2

Latin American volcanoes with ice caps and major lahar hazard

Name	Elevation (m)	Snowline (m)	Year of known lahar-producing eruptions
Popocateptl (Mexico)	5452	4700	
Pico (Mexico)	5675	4700	
Herveo (Colombia)	5590	4800	
Ruiz (Colombia)	5389	4800	1595, 1845, 1985
Tolima (Colombia)	5215	4800	
Huila (Colombia)	5750	4500	
Antisana (Ecuador)	5705		
Cotopaxi (Ecuador)	5897	4600	25 eruptions, last in 1877
Tungurahua (Ecuador)	5016	4600	
Sangay (Ecuador)	5230		
Coropuna (Peru)	6425		
Sabancaya (Peru)	5795		
Misti (Peru)	5825		
Ubinas (Peru)	5672		
Tutupaca (Peru)	5806		
Ticsani (Peru)	5415		

Northern Chile has ~ 40 volcanoes > 5,000 m elevation.

Figure Captions

Figure 1. Distribution of active volcanoes in Latin America (from Morris et al. 1979).

Figure 2. The village of Naranjo, 8 km from the summit of El Chichon volcano, showing the effects of the pyroclastic surge which inundated the area during the second major 1982 eruption on 4 April. Most wooden structures were blown down and burned by the force and heat of the surge cloud. The passage of the surge left only a thin, 3 cm thick deposit of sandy tephra.

Figure 3. The city of St. Pierre, Martinique after destruction by pyroclastic surges from the May 8, 1902 eruption of Mount Pelee.

Figure 4. Isopach map of the tephra fall deposit from the13 November, 1985 eruption of Nevado del Ruiz . Isopach contours are in millimeters. Solid circles with no thickness values are locations where the fall deposit was present only as a discontinuous accumulation of tephra.

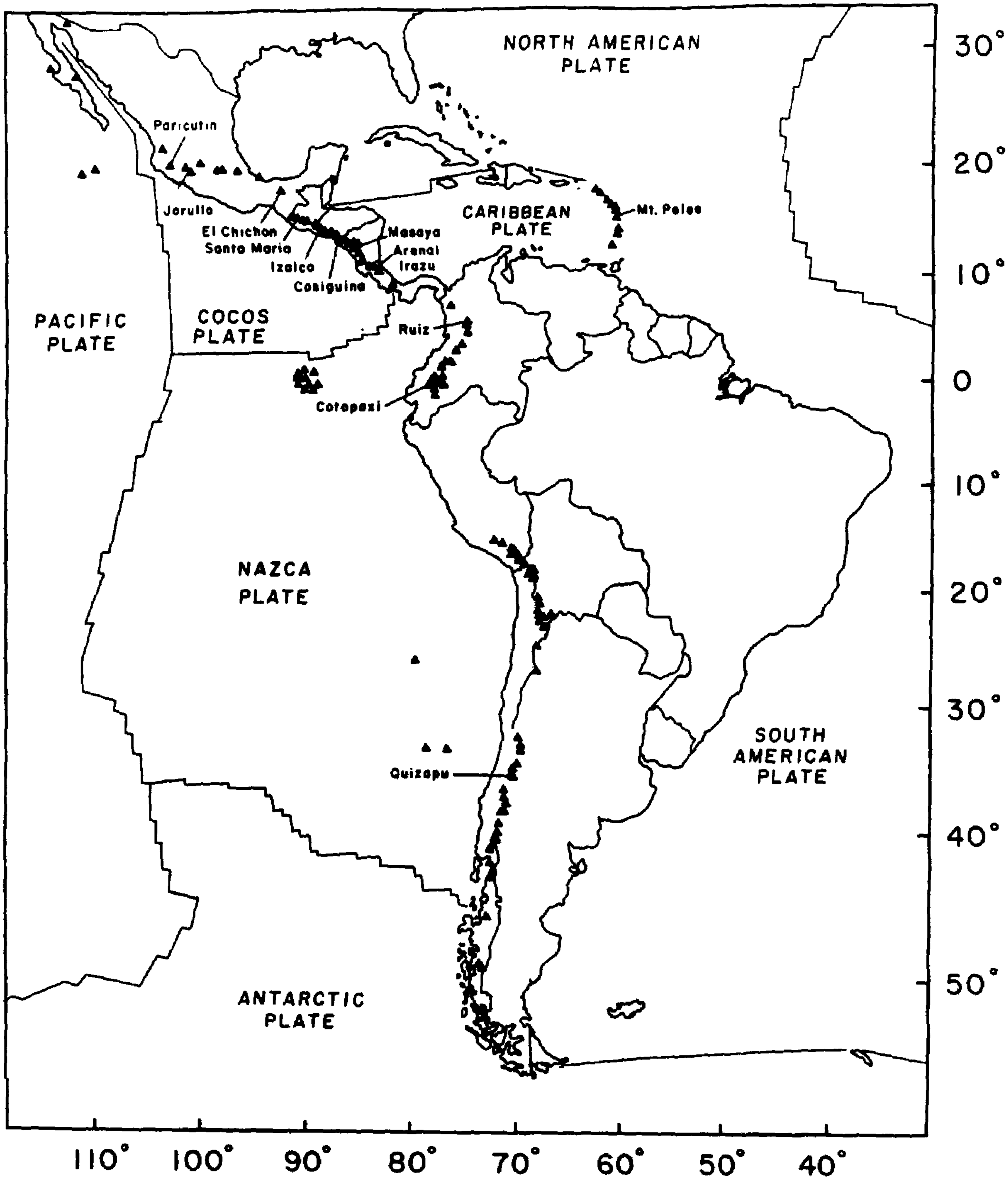
Figure 5. Distribution of lahar deposits (solid black pattern) from the 13 November 1985 eruption of Nevado del Ruiz, Colombia.

Figure 6. Areal view of the destruction caused by lahars in the town of Armeo, 50 km east of Nevado del Ruiz. Note that many of the buildings were sheared off at the base and only their foundations remain.

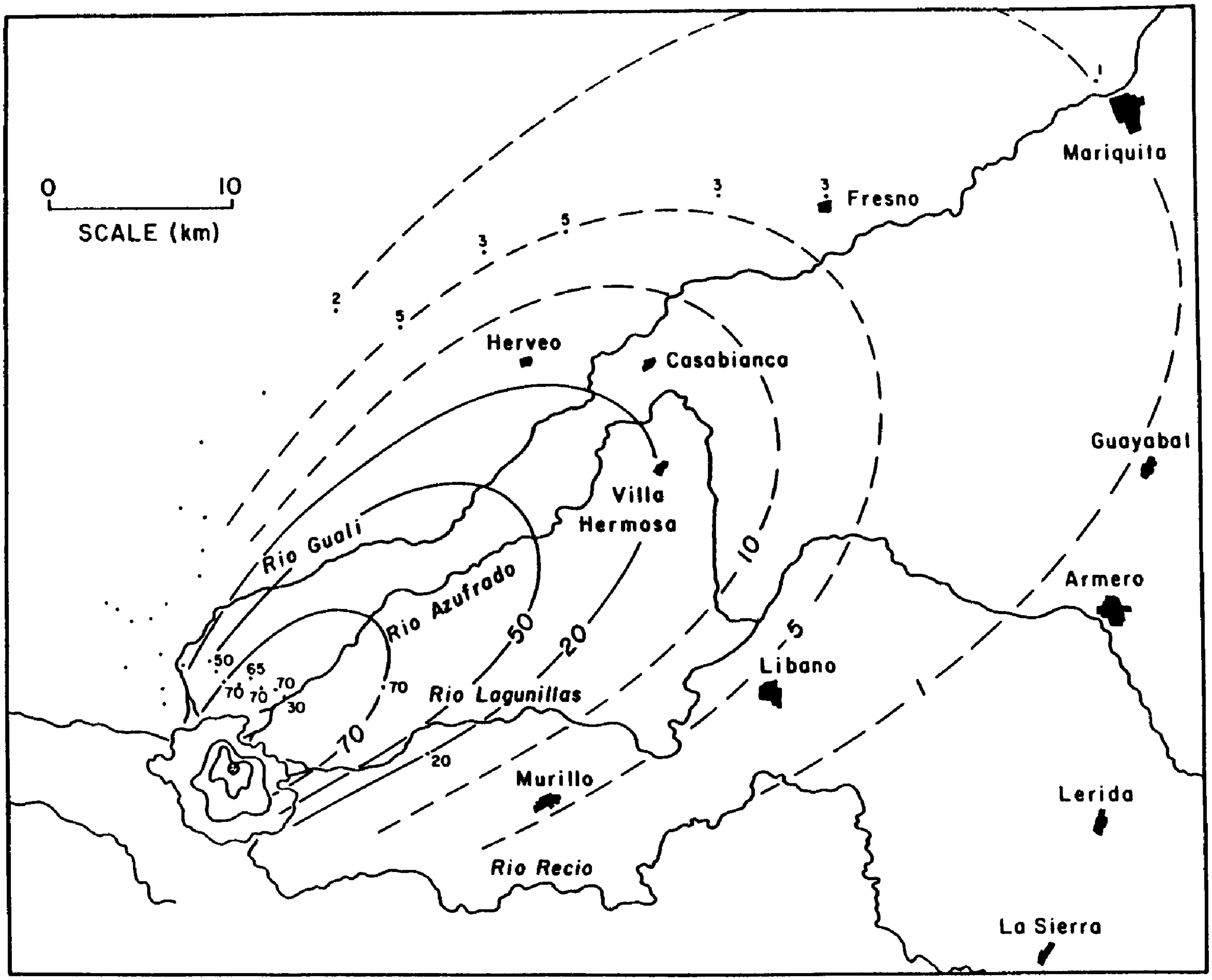
Figure 7. Splash marks left by lahars on the sides of houses in the town of Honda, 80 km ENE of Nevado del Ruiz.

Figure 8. A schematic diagram of the generation of lahars or mudflows during the 1985 Ruiz eruption in Colombia. The base of the eruption column, generated by the explosive eruption, was surrounded by a turbulent density current of hot pyroclastic materials, including pumice and volcanic ash, which generated surges and pyroclastic flows over the glacier surface. The heat

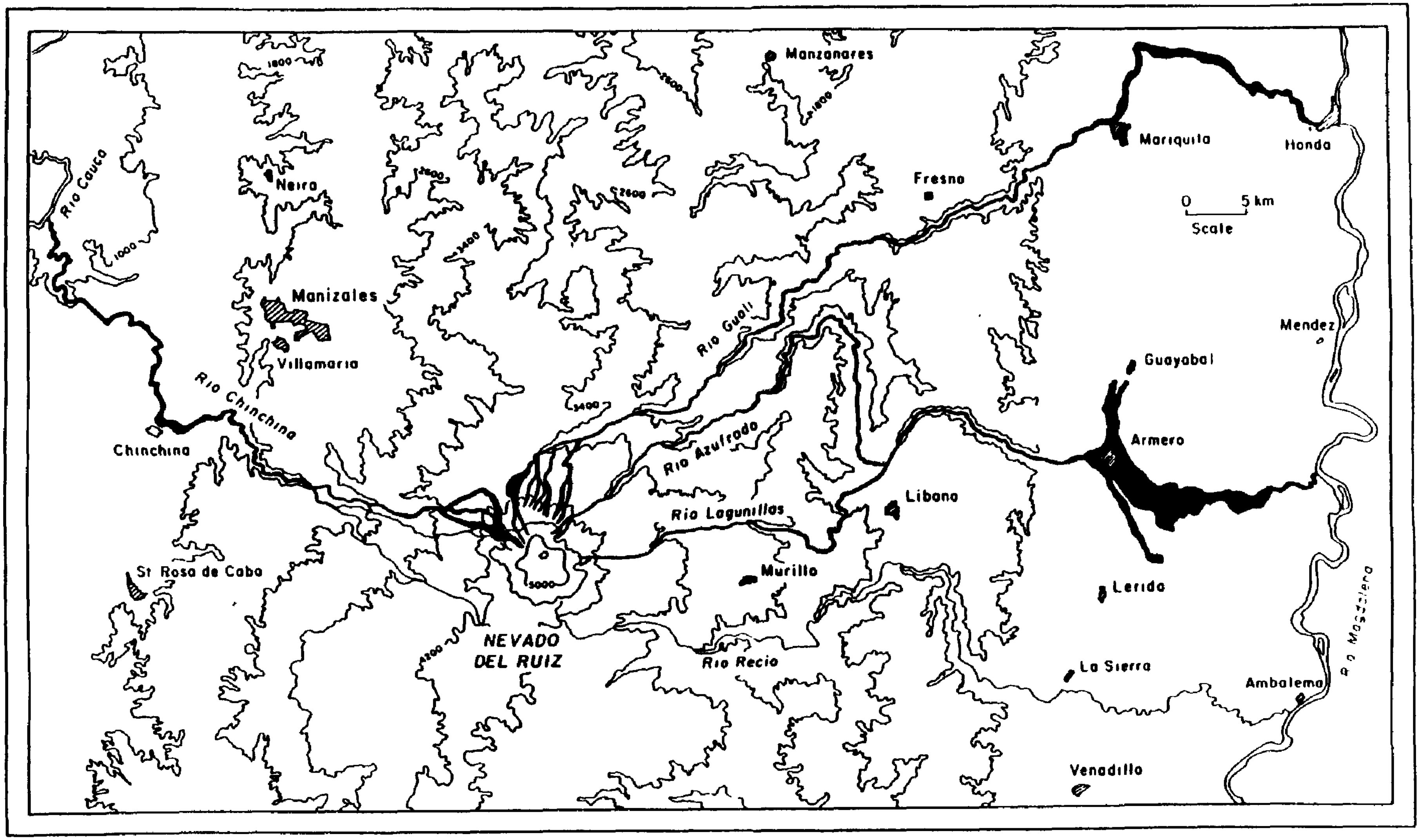
transmitted from the hot surges led to melting of the glacier surface, generating large-scale floods of meltwater down the volcano's flanks. The floods channelled into the major river valleys, where they eroded the soil and surface sediments, resulting in the formation of lahars or dilute mudflows. During the initial explosive event, the eruption column reached altitude of 30 km, and fallout of tephra from the plume formed a thin pumice and volcanic ash deposit down-wind of the volcano.



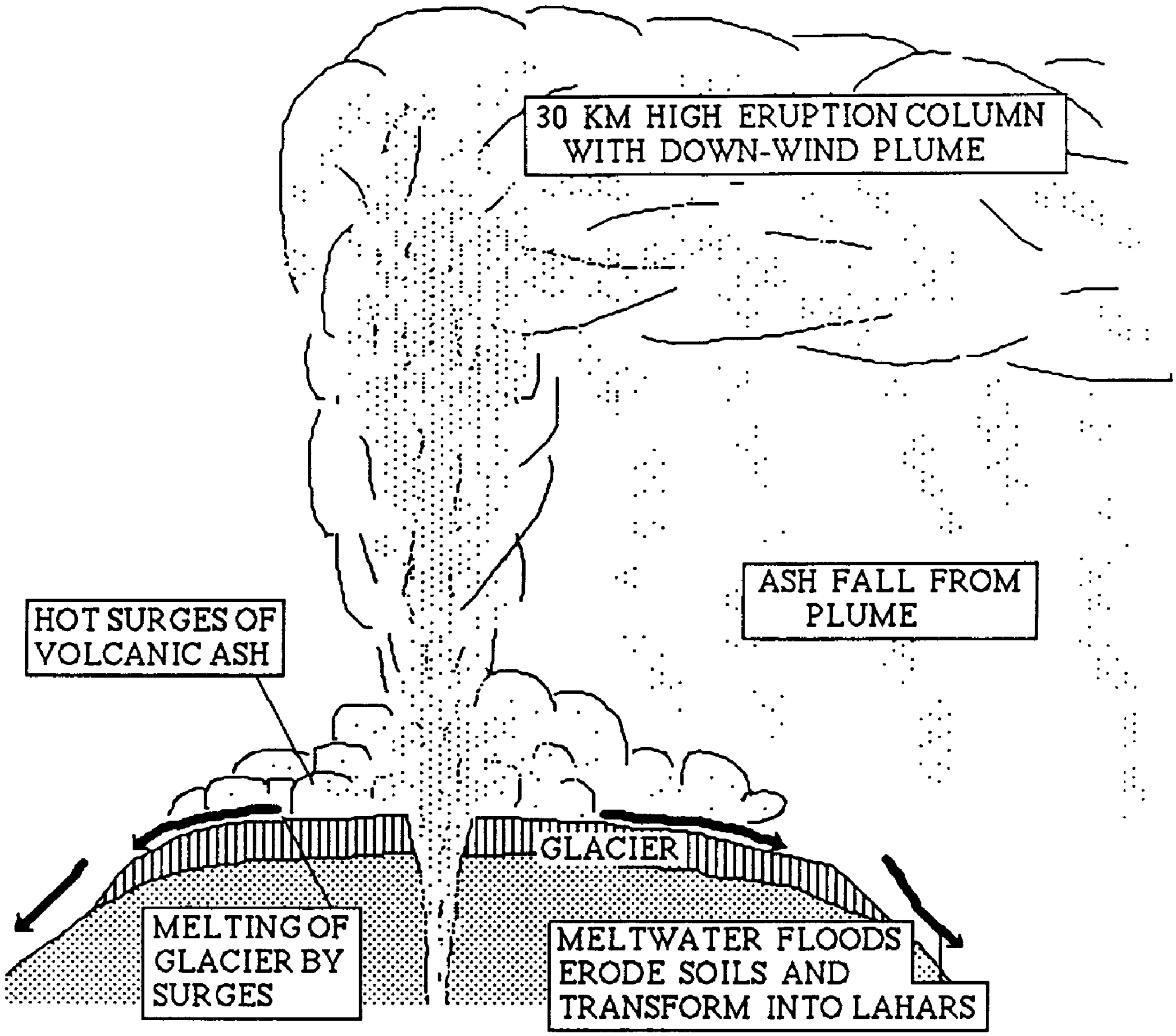
NORTH AMERICAN PLATE
CARIBBEAN PLATE
PACIFIC PLATE
COCOS PLATE
NAZCA PLATE
SOUTH AMERICAN PLATE
ANTARCTIC PLATE
Paricutin
Jorullo
El Chichon
Santa Maria
Izalco
Cosiguina
Masaya
Arenal
Irazu
Mt. Pelee
Ruiz
Cotopaxi
Quizapu
30°
20°
10°
0
10°
20°
30°
40°
50°
110°
100°
90°
80°
70°
60°
50°
40°



0 10
SCALE (km)
Mariquita
Fresno
Herveo
Casabianca
Villa Hermosa
Guayabal
Armero
Libano
Murillo
Lerida
La Sierra
Rio Guali
Rio Azufrado
Rio Lagunillas
Rio Recio



Manzanares
Mariquita
Honda
Fresno
0 5 km
Scale
Rio Cauca
Neira
Manizales
Villamaria
Rio Gualí
Mendez
Guayabal
Armero
Chinchina
Rio Chinchina
Rio Azufrado
Libano
Rio Lagunillas
St Rosa de Cabo
Murillo
Lerida
NEVADO
DEL RUIZ
Rio Recio
La Sierra
Ambalema
Venadillo
1800
2600
1000
3400
5000


30 KM HIGH ERUPTION COLUMN
WITH DOWN-WIND PLUME
ASH FALL FROM
PLUME
HOT SURGES OF
VOLCANIC ASH
GLACIER
MELTING OF
GLACIER BY
SURGES
MELTWATER FLOODS
ERODE SOILS AND
TRANSFORM INTO LAHARS