Reports

Eruption of the Nevado del Ruiz Volcano, Colombia, On 13 November 1985: Tephra Fall and Lahars

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A small Plinian eruption of the Nevado del Ruiz volcano in Colombia ejected 3.5×10^{10} kilograms of mixed dacite and andesite tephra on 13 November 1985, with a maximum column height of 31 kilometers above sea level. Small pyroclastic flows and surges, generated during the initial stage of the eruption, caused surface melting of approximately 10% of the volcano's ice cap, leading to meltwater floods. The erosive floods incorporated soils and loose sediments from the volcano's flanks and developed into lahars, which claimed at least 25,000 lives.

The 13 November 1985 eruption of the Nevado del Ruiz volcano in Colombia is the largest volcanic disaster since the 1902 eruption of Mount Pelée in Martinique, when 28,000 people were killed. Ruiz had erupted in 1595, 1828–29, 1832–33, and also in 1845; lahars (mudflows of volcanic debris) caused 1000 casualties in 1845 (*1–4*). Precursory activity began in November 1984, with a series of earthquakes up to magnitude 4 (*5*). On 11 September 1985, a small phreatic explosion occurred, causing minor ashfall up to 35 km west and northwest of the volcano. This activity also triggered a small lahar, which traveled 27 km down the north flank of the volcano.

The chronology of the 13 November 1985 eruption has been reconstructed largely from eyewitness reports. At about 3 p.m. on 13 November (all times local), a small explosion was observed in the Arenas crater that caused minor ashfall in the northern towns of Fresno and Mariquita at about 4 p.m. and in Honda at about 5 p.m. (Fig. 1). At 9:09 p.m. on the same day, the main explosive eruption began, producing a Plinian eruption column that was sustained for about 20 minutes, but was punctuated by two large explosions. Fall of tephra from the main eruption began at about 9:30 p.m., 20 km north and northeast of the volcano, and was most intense about 10 p.m. but ceased shortly after midnight. A normally graded tephra fall layer deposited northeast of the volcano could be traced up to 80 km from the source (Fig. 1). The dispersal of tephra was, however, much more extensive during the eruption, and minor ashfall was reported more than 400 km northeast of the volcano. Close to the source, the fall deposit consists of about 80% andesitic and dacitic pumice, with some banded pumice and about 20% lava lithics. The banded pumice contains andesitic and dacitic components (about 60 and 63% by weight SiO_2, respectively), indicating magma mixing before or during eruption. Dacitic pumice is dominant in distal areas, whereas darker and more dense andesitic pumice is common close to the crater. Coarse-grained pumice, which was sufficiently hot to scorch vegetation, fell 5 km north of the crater. The deposit is well sorted throughout and shows only a moderate degree of fragmentation. No accretionary lapilli were observed.

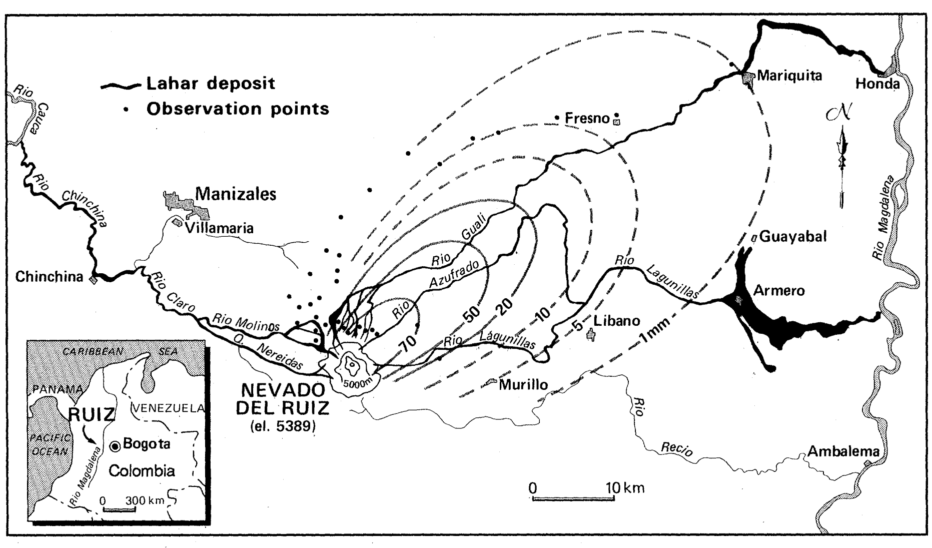

Fig. 1. Distribution of tephra fall and lahar deposits from the 13 November 1985 eruption of the Nevado del Ruiz volcano. Lahars are black. Isopachs of the tephra fall are in millimeters and are shown by dashed and solid lines. Inset shows the location of Ruiz in Colombia.

The diameters of the five largest pumice and lithic clasts were measured at 47 sites downwind of the volcano. Maximum lithic isopleths are shown in Fig. 2. A maximum column height of 31 km above sea level can be estimated on the basis of the geometry of a lithic isopleth 3.2 cm in diameter (*6*), indicating injection of some tephra into the stratosphere. These results are supported by the appearance of an aerosol layer between 24 and 29 km over Mauna Loa in Hawaii on 26 November (*7*) and the detection of a westward-drifting stratospheric plume by the Nimbus 7 satellite (*8*). It is likely, however, that the northeasterly tephra dispersal, which generated the fallout deposit, was governed primarily by upper tropospheric winds. If we assume there was a tropical temperature lapse rate and an estimated magma temperature of 800°C, a 31-km column height would correspond to a maximum mass eruption rate of 5×10^7 kg/sec (*9*). The volume of tephra within the 1-mm isopach of the fall deposit is 2.9×10^7 m^3. By analogy with the May 1980 fall deposit of Mount St. Helens, in the United States, where 25% of the total deposit was outside the 1-mm isopach (*10*), we estimate total erupted volume of 3.9×10^7 m^3. With a bulk density of 900 kg/m^3, the fall deposit represents a total erupted mass of 3.5×10^{10} kg. Based on a duration of 20 minutes, the average mass eruption rate was 3×10^7 kg/sec, in reasonable agreement with the estimated maximum eruption rate.

The eruption also generated minor pyroclastic surges and flows, but the details of

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their timing, distribution, and origin are poorly known. A pyroclastic surge that had traveled about 2 km across the glacier destroyed the Refugio building on the west slope of Ruiz at an elevation of about 4800 m. 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, about 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, and capped by a minor fall deposit. Minor pyroclastic flow and surge activity therefore occurred at the onset of the eruption and preceded the tephra fall.

Three major lahars issued onto the lowlands surrounding the Ruiz volcano, after a drop in elevation from the summit of about 4 km (Fig. 1). In the canyons and steep river valleys, the lahars were erosive and left insignificant deposits. The flows typically eroded down to bedrock and left a trimline at 20 to 30 m above normal river level. In lower parts of the valleys the lahars deposited a thin veneer (50 cm) of poorly sorted sediment, which was largely derived from erosion of soils from the volcano's slopes and the river valleys. A lahar in the Guali River from the north flank of Ruiz reached the outskirts of Mariquita at 11:30 p.m. on 13 November and reached Honda at 2 a.m. the following morning, after 90 km of flow (Fig. 1). In the headwaters of the Guali River the watery flood washed tephra fall off of vegetation, indicating that this event was generated after the initial tephra fall. Near Mariquita, the Guali lahar, when active, was up to 8 m thick and 250 m wide. Because of its high fluidity, the lahar spread out leaving a deposit, which ranges from 1 m in the center of the flow channel to 0.5 m at the margins. Boulders are concentrated in the center of the deposit, often 1 to 2 m in diameter, and seldom up to 6 m. A minimum velocity of flow of 28 km/hour can be calculated for this lahar, from source to Mariquita, assuming that it was initiated at the time of the explosive eruption. During its flow from Mariquita to Honda, the Guali lahar slowed down to 9 km/hour and deposited much of its load in a 1- to 2-m-thick layer as it flowed over gentler slope. The lahar was still highly destructive in Honda, however, where it rose 5 m above the normal level of the Guali River, destroying more than 20 houses and claiming at least two lives.

On the east flank of the volcano, a lahar from the headwaters of the Lagunillas valley joined with a lahar in the Azufrado valley from the northeast flank of the volcano (Fig. 1). The combined lahar inundated the town of Armero at about 11 p.m., killing most of the population of 25,000. As the lahar emerged from the Lagunillas valley, it branched into three lobes. One lobe flowed 6 km north, toward the town of Guayabal; the principal lobe continued directly east through Armero, and the smallest lobe flowed southeast along the Lagunillas riverbed. The deposit of the distal lobes is yellowish-brown, fine-grained, and seldom more than 0.5 m thick; it typically has scalloped edges. In the principal axis of the lahar and toward the Lagunillas canyon, the deposit thickens to 3 to 4 m and is markedly coarser grained, with large boulders along the center of flow. The Lagunillas-Azufrado lahar, which destroyed Armero, was a complex event, and its character was probably affected by the presence of a lake that had recently formed behind a landslide dam in the lower part of the Lagunillas River, above Armero. The reports of survivors from Armero indicate that the lahar came in two or three waves. The character of the lahar around Armero also shows that two deposits can be recognized. The distal part of the lahar, for example, near Guayabal, is thinner, buff to yellowish-brown, and appears to have been a more dilute flow, whereas the central part of the lahar over the town of Armero is a dark gray, coarser grained, and thicker deposit.

We propose that the first lahar wave to affect Armero was derived initially from the Lagunillas valley, 60 km from Armero. The bursting of the natural dam in the Lagunillas River may have contributed to this lahar. Although probably generated at the same time, the Azufrado lahar had a greater flow distance (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. The Azufrado lahar was therefore initiated during tephra fall (about 9:10 p.m.) and arrived in Armero at about 11 p.m., after flowing 70 km, indicating an average velocity of 38 km/hour.

Table 1. Area and volume of 1985 lahar deposits from the Nevado del Ruiz volcano.

River system	Area (km^2)			Volume* ($\times 10^7$ m^3)
	Slopes	Plains	Total	
Guali	7.7†	10.8‡	18.5	0.5 to 1
Lagunillas/Azufrado	10.9†	38.0‡	48.9	2 to 4
Chinchina	5.4§	9.0‖	14.4	0.5 to 1
Total	24.0	57.8	81.8	3 to 6

*Volume calculations based on an average deposit thickness of 0.5 to 1.0 m and an area of deposition restricted to the gentle plains beyond the volcano. †Elevations above 600 m. ‡Elevations below 600 m. §Area above the junction of Claro and Chinchina rivers. ‖Area between junction of Claro and Chinchina rivers and the Cauca River.

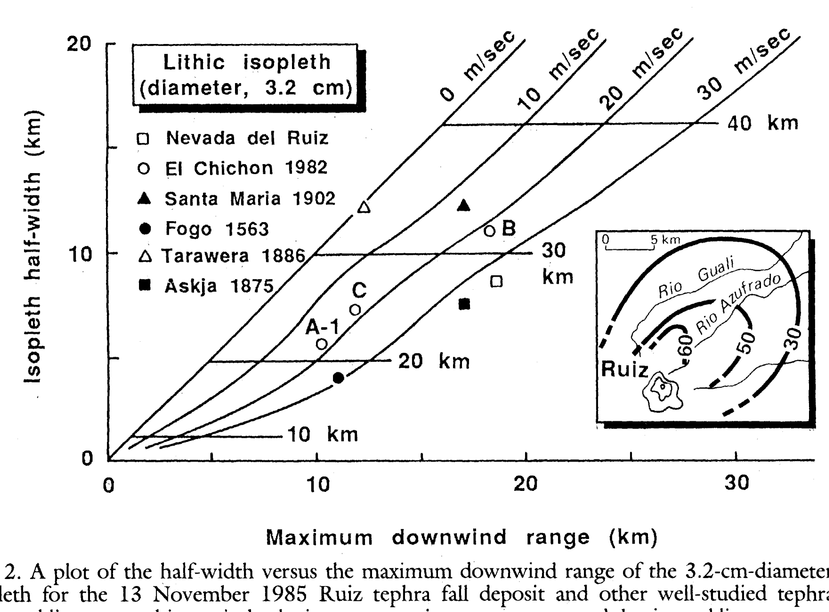

Fig. 2. A plot of the half-width versus the maximum downwind range of the 3.2-cm-diameter lithic isopleth for the 13 November 1985 Ruiz tephra fall deposit and other well-studied tephra falls. Diagonal lines are ambient wind velocity contours, in meters per second; horizontal lines are maximum eruption column height (in kilometers); A-1, B, and C refer to the three major eruptions of El Chichon. Inset shows the distribution of lithic isopleths in the 1985 Ruiz fall deposit (in millimeters).

On the west flank of Ruiz, a lahar flowed down the headwaters of the Molinos River and into the Chinchina River. It affected low-lying parts of the town of Chinchina about 10:30 p.m., with a loss of about 1000 lives, and it continued the length of the Chinchina River to the Cauca River after flowing 60 km. 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 began during deposition of the tephra fall layer on the volcano. The minimum velocity of the Chinchina lahar is estimated as 22 km/hour.

The lahar deposits were mapped from a helicopter at a scale of 1:25,000 and examined on the ground at several localities. Estimated total volume of the lahar deposits is 3×10^7 to 6×10^7 m^3 (Table 1). One week after deposition, the lahars were still water-rich (35% water by volume). Several features indicate, however, that they were much more water-rich at the time of flow. Extensive drainage channels beyond the ends of the flow lobes indicate large-scale dewatering after deposition. Splash marks on walls many meters above the flow level in Chinchina and Honda indicate jets and fountaining from a dilute flow. The lahars were sufficiently dilute and fluid to maintain flow on very low slopes in meandering river channels, without significant deposition. The sedimentary features of the deposit indicate deposition from hyperconcentrated flood flow (*11*), and thus we infer original solid contents of 35 to 65% by volume. On the basis of these estimates, the total water volume transported from the volcano by lahars was of the order 1×10^7 to 6×10^7 m^3.

The principal source of water lies in the glacier of the Ruiz volcano, with an estimated volume of 3×10^8 m^3 before eruption. The contribution of normal river runoff to the lahars must have been minor. One week after the eruption we estimated the maximum Guali River flow as 30 m^3/sec. During the 2-hour lahar event, the contribution of water to the Guali lahar owing to river runoff could therefore be a maximum of 4×10^5 m^3, or only 20% of the mass of water estimated in the Guali flood. These figures suggest that the recent activity led to melting of 5 to 15% of the volume of the glacier.

Evidence of high fluidity in the Ruiz lahars suggests a high ratio of water to sediment. Factors that contributed to this situation include a relatively small volume of available pyroclastic material and a large volume of water derived by melting of glacial ice. Indeed, most of the sediment in the lahars was incorporated by erosion of loose soil in the river valleys, and the amount of primary eruptive material is minor. The lahars thus began in the headwaters of the rivers as sediment-starved floods that increased their sediment load at lower elevations by erosion. Derivation of the bulk of the sediment by erosion in the lahar channels on the volcano's slopes (24 km^2; Table 1) implies average erosion of a 1- to 2-m-thick layer in the channels. Generation of meltwater probably occurred by several processes, including glacial surface melting by hot tephra fall, pyroclastic flows and surges, subglacial melting by geothermal activity, and melting in glacial avalanches during breakup 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, contributing to the Azufrado and Lagunillas floods. However, no blocks of ice were observed in the lahar deposits; in the 1845 eruption, ice from the glacier was carried by lahar to the Magdalena River (*2*).

Assuming that the majority of the 1×10^7 m^3 to 6×10^7 m^3 of water in the lahars was derived from melting of the glacier, we can quantitatively evaluate the processes of melting and the sources of heat. Melting from tephra fall on ice must be considered minor because of the small volume of tephra fall and the limited surface area of the glacier (20 km^2). For example, if the glacier were covered by a 0.5-m-thick, coarse-grained fall deposit, with clasts initially at 400°C, and if half of the thermal energy were used 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 (*12*). Lahar generation by gravity currents of steam and pyroclasts has been observed, for example, during the 1947 Plinian eruption of Hekla in Iceland (*13*) and the 18 May 1980 eruption of Mount St. Helens (*14*). 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 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, and the meltwater was catastrophically released during the eruption. Such discharges are common in Iceland where they are known as jokulhaup (*15, 16*). They contain about 85 to 90% water by volume and are thus analogous to hyperconcentrated flood flows. Although there is no direct evidence as yet for jokulhaup-like discharges at Ruiz, all of the conditions necessary for such activity were present.

Our study indicates that the eruption column from the main explosion of Ruiz volcano on 13 November 1985 first generated a small pyroclastic flow and surge that advanced over the glacier to the west and north, causing extensive surface melting. Simultaneously, the eruption evolved into a high Plinian column, up to 27 km above the volcano. During the fallout of tephra from the Plinian column, floods of meltwater ran off the glacier into headwaters of rivers draining the north, east, and west slopes of the volcano. The sediment-starved floods contained negligible juvenile tephra, but they eroded the soil layer and other superficial sediments off the flanks of the volcano and developed into lahars.

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12. As a simplifying assumption, the passage of a pyroclastic surge of ice has been modeled as a gravity current of steam (viscosity is 1.3×10^{-5} Pa sec; thermal conductivity is 0.024 W m^{-1} K^{-1}; and specific heat is 1.25×10^3 J kg^{-1} K^{-1}). The steady-state melting rate of the ice surface (heat of fusion is 3.3×10^5 J kg^{-1}) has been calculated by using equations for heat transfer during forced convection modified by H. Huppert *et al.* [*Nature (London)* **309**, 19 (1984)]. Very low values of melting, 2.5×10^{-4} m/min, are obtained because of the low thermal conductivity and Prandtl number of steam. These calculations do not, however, consider the effect of condensation within the boundary layer and the consequent release of the heat of vaporization (2.4×10^6 J kg^{-1}). Consequently, experiments were conducted with the passage of a steam jet (temperature = 100°C; $R_e = 1 \times 10^6$) over ice at 0°C, and a steady-state melting rate of 2×10^{-2} m/min was determined (ice surface slope of 10°). This is likely to be a minimum melting rate compared to a pyroclastic surge, which contains hot pyroclastic fragments that would both thermally and mechanically erode the surface of ice.
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17. We thank P. M. Jaramillo, E. Parra, F. Zambrano, and other members of the Comite de Estudios Vulcanologicos Comunidad Caldense for logistical support. Helicopter transport was provided by the Colombian Air Force and the U.S. Army. We are grateful to M. L. Calvache for collaboration in mapping of lahar deposits. H.S. and S.C. were supported by National Science Foundation grant EAR-8306384.

10 December 1985; accepted 11 June 1986