Volcanic eruptions with little warning: the case of Volcán Reventador's Surprise November 3, 2002 Eruption, Ecuador

Minard Hall
Patricio Ramón
Patricia Mothes

Instituto Geofísico, Escuela Politécnica Nacional, Quito, Ecuador
mhall@igepn.educ.ec
pramon@igepn.educ.ec
pmothes@igepn.educ.ec

Jean Luc LePennec

Institut de Recherche pour le Développement
lepennec@ird.fr

Alexander García
Pablo Samaniego
Hugo Yepes

Instituto Geofísico, Escuela Politécnica Nacional, Quito, Ecuador
agarcia@igepn.educ.ec
psamaniego@igepn.educ.ec
hyepes@igepn.educ.ec

ABSTRACT

Successful mitigation of a possible volcanic disaster depends upon the early detection of renewed volcanic activity. With considerable optimism, volcano observatories instrument dangerous volcanoes, with the hope of an early recognition of the reactivation of a volcano. Reventador volcano's November 3, 2002 eruption came with little warning and had a tremendous socio-economic impact. Reventador volcano, a young andesitic cone in the Eastern Cordillera of Ecuador, has had, at least, 16 eruptions between 1541 and 2002. These eruptions were characterized by small pyroclastic flows, blocky lava flows, debris flows, and limited ash falls. With the exception of a M=4 earthquake near the volcano one month earlier, only seismic activity related to the eruption onset was registered. Following only 7 hours of seismic tremor, the paroxysmal eruption began at 0912 h on November 3, 2002 with a sustained column that ascended to 17 km and five pyroclastic flows, that traveled as much as 9 km to the east. By mid-afternoon ash falls of 1-10 mm thickness began blanketing the Interandean Valley near Quito. The economic impact was significant, including severe damage to the principal petroleum pipelines, closure of schools, businesses, and Quito's airport for 10 days. It is important to conclude that for those volcanoes that are characterized by low silica, volatile-rich, fluid magmas, magma ascent can be aseismic, rapid, and without much warning. This event should serve as a clear reminder to scientists, civil defense, and authorities of the rapid onset of the eruptions of some volcanoes.

Key words: Reventador volcano, Ecuador, Eruption with little warning.

RESUMEN

Erupciones volcánicas con poco aviso: el caso de la erupción sorpresiva del 3 de Noviembre del 2002 del Volcán Reventador. La mitigación exitosa de un posible desastre volcánico depende de la detección oportuna de la reactivación de un volcán. Con mucho optimismo, los observatorios volcánicos efectúan un monitoreo de volcanes peligrosos, en espera de reconocer tempranamente el inicio de nueva actividad. La erupción del volcán

Reventador, el día 3 de Noviembre de 2002, comenzó con poco aviso. El volcán Reventador es un volcán joven andesítico de la Cordillera Oriental del Ecuador que ha tenido, al menos, 16 erupciones desde 1541. Dichas erupciones fueron caracterizadas por flujos piroclásticos y lávicos, flujos de escombros y caída limitada de ceniza. Con la excepción de un fuerte sismo cerca del volcán un mes antes, se registró solamente la sismicidad que comenzó el proceso eruptivo. Luego de 7 horas de 'tremor' sísmico, la erupción paroxismal empezó a las 0912 h de ese día con una columna sostenida que ascendió a los 17 km y con cinco flujos piroclásticos que viajaron hasta 9 km al este. Antes de las 1500 h empezó a caer ceniza en el Valle Interandino cerca de Quito, formando una película de 1 a 10 mm de espesor. El impacto económico fue grande, pues resultó en graves daños a los oleoductos y el cierre de colegios y negocios y del aeropuerto de Quito durante 10 días. Hay que concluir que en aquellos volcanes que aportan magmas de bajo contenido de sílice, ricos en gases y muy fluidos, el ascenso del magma en el conducto puede ser asísmico, rápido y sin aviso. Así, esta erupción es muy útil para recordarle a los científicos, la defensa civil y a las autoridades que algunos volcanes pueden reactivarse con erupciones violentas, sin mayor aviso.

Palabras claves: Volcán Reventador, Ecuador, Erupción con poco aviso.

INTRODUCTION: THE PROBLEM

Successful mitigation of a possible volcanic disaster depends upon adequate monitoring and early detection of renewed volcanic activity. With considerable optimism, volcano observatories throughout the world instrument dangerous volcanoes and attempt to establish the volcano's background activity, with the hope of recognizing in a timely fashion the onset of valid precursory activity that would signal a reactivation of the volcano.

However, not all volcanoes -not even well instrumented ones - may show a slow, progressive buildup of precursory activity prior to entering into eruption. Redoubt's 1989, Galunggung's 1982, and Mayon's 1968 and 1984 eruptions began with only a few hours of precursory seismic activity. As it will be discussed here, Reventador's November 3, 2002 eruption came with little warning and resulted in a tremendous social-economic impact for Ecuador.

REVENTADOR VOLCANO'S SETTING

Reventador volcano is a young andesitic cone situated in the western corner of an older caldera, one of many volcanic edifices that comprise the Eastern Cordillera of Ecuador's volcanic arc (Hall, 1977; Pichler *et al.*, 1976; Aguilera *et al.*, 1988). The horseshoe-shaped avalanche caldera has diameters of 4 km (north-south) and 6 km (northwest-southeast) and is breached on its east-southeast side (Fig. 1) (INECEL, 1988). Various streams leave the caldera and descend 4 km southeastward to the nearby Coca river. The interior walls of the caldera are very steep and have heights that range from 50 to 400 m above the southeast-sloping floor of the amphitheater. Older somma rims are recognized on the outer western flank of the edifice, whose total diameter is approximately 16-20 km (Figs. 1, 2B). Although no towns are located nearby, the principal highway to Ecuador's oil fields, as well as two crude oil pipelines and one refined products pipeline, are built upon the Coca river floodplain at the eastern foot of the caldera; this infrastructure was severely damaged by the 2002 eruption. Heavy rainfall and dense cloud forest vegetation characterize the region and limit accessibility.

The young cone has a symmetrical shape with steep slopes of up to 34 degrees (Fig. 2A). Eruptive products from the volcano are slowly filling the caldera, especially the laharic deposits along the caldera's northern and southern limits. Older lava flows that originated in the summit crater or from flank vents are observed everywhere within the caldera and down to the Coca river. Prior to the 2002 eruption, the cone had a height of 3,560 m, 1,500 m above the lowest eastern part of the caldera floor (2000 m); as such, it was slightly higher than the nearby western caldera rim. An elongate crater, approximately 200 m long, adorned the summit and was characterized by mild, but persistent fumarolic activity during the past 26 years.

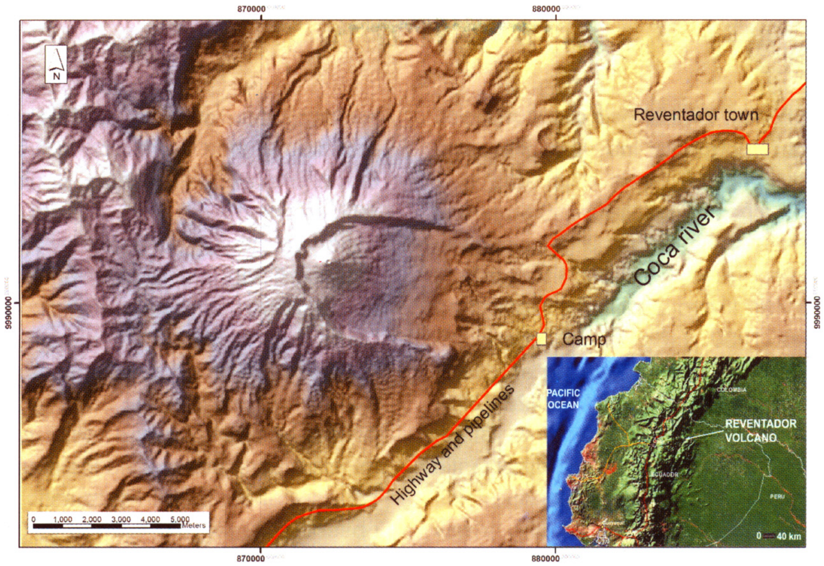

FIG. 1. Location map for Reventador volcano and its relationship to the highway, pipelines, and the town of Reventador.

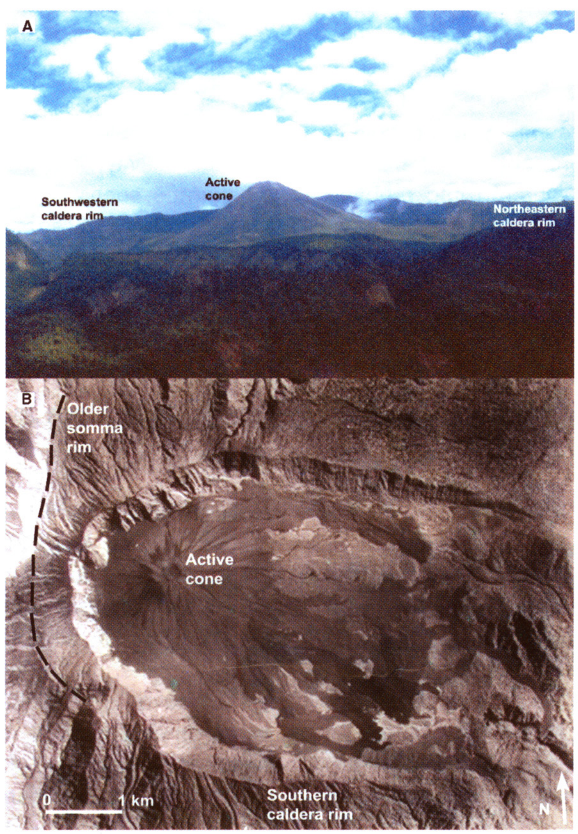

FIG. 2. **A.** 1987 view of the young cone with the southwestern rim of the caldera at the back and its northeastern rim at the front. Taken from the east. The cone is about 1.5 km high; **B.** Aerial photograph of the caldera and young cone. North is upward in the photograph and the caldera drains to the right southeastward. The photograph shows lava flows of the 1944's and 1970's.

PAST VOLCANIC HISTORY

The detailed history of this volcano is not well known, due to its remoteness, inaccessibility, and persistent cloudy weather. It is estimated that Reventador volcano has had, at least, 16 eruptions between 1541 and 2002 that were large enough to have been detected in the populated Interandean Valley, some 70 - 90 km to the west (Hantke and Parodi, 1966; Hall, 1980; J. Egréd, oral communication, 2003). During the XX century, eruptions were reported in the period 1898-1912, 1926-1929, 1944, 1958-1960, 1972, 1973-1974, and 1976. These eruptions were characterized by small pyroclastic flows, blocky lava flows, moderate-size debris flows (lahars), and ash falls that deposited only a few millimeters of ash in the Interandean Valley.

While little is known about possible precursory activity of previous eruptions, the 1976 eruption does provide some insight into the reactivation process. Following small Volcanic Explosivity Index (VEI, Newhall and Self, 1982), 3 eruptions in July-September 1972 and November 1973-April 1974, which were characterized by lava flows of 10.5 and 3.8 million m^3 (Hall, 1980), respectively, in addition to moderate ash falls and probable 'nuee ardente' flows, Reventador volcano entered into eruption again in January 1976. This was preceded in August 1975 by steam emission lasting several hours that vented from warm springs, 9 km distant, which in hindsight suggests that this event was the result of pressurization of the local hydrothermal system, probably related to magma intrusion (C. Newhall, oral communication, 2004). Beginning in October 1975 a steam column, at least, 1 km high was observed issuing continuously from the crater up until the 5 January 1976 eruption. At that time, the volcano was not monitored and consequently there exists no seismic documentation.

The 1976 eruption was accompanied by a high ash column, pyroclastic flows, and two large lava flows. The lava flows had a total volume of about 20 million m^3 and descended the southeast side of the cone for about 5 km. Pyroclastic flow activity was observed during the second to third week of the eruption, generally small flows that traveled only 2-3 km from the crater. Debris flow deposits were seen everywhere. There were no casualties or damage to the pipelines, as most flows never reached the roadway or the pipelines, 9 km away (Fig. 1) (Hall, 1976, unpublished report).

Given the high rainfall and the water-saturated subsoil, it was expected that increased steam emission would generally announce impending volcanic activity, once the magma was approaching the surface; such was the case in late 1975. Prior to the November 2002 eruption, the authors anticipated that large-scale steam venting as well as progressive seismic activity, would be the chief precursory warnings, if this volcano were entering into eruption.

ERUPTION CHRONOLOGY - 3 TO 21 NOVEMBER 2002

PRECURSORY ACTIVITY

The first clear precursor activity that preceded the eruption was a M=4.1 volcano-tectonic (VT) earthquake that occurred on October 6, 2002 and was accompanied by 9 smaller VT events. Their epicenters were located on the lower SW flanks of the old edifice and their hypocenters were placed at depths of 10-11 km. Because this same area is traversed by numerous regional faults belonging to the active thrust belt that runs along the eastern foot of the Andes, these seismic events were interpreted to be related to that fault system. No other seismic activity was registered in the area prior to 3 November, nor were there anomalous superficial manifestations. About October 20, a local guide with tourists reached the top of the cone and reported only normal fumarolic activity. In addition no anomalous activity was detected either by local residents or by satellite monitoring during this period.

On November 3, 2002 between 0200 and 0300 h (all times are local = EST) a continuous low amplitude tremor (0.7-1.0 Hz) was detected and continued for many hours. Beginning around 0300 h a seismic swarm of >100 events began of both VT and hybrid tendency which were superimposed upon the ongoing tremor. Workers at a nearby construction camp, 8 km east of the crater, were awakened by the earthquakes. At daylight (0530-0600 h) they reported a steam column 2-3 km high above the cone. By 0715 h the steam and ash column was high enough to be reported by airplane pilots flying between Quito and Guayaquil (estimated at 3-4 km above the cone). The first NOAA (National Oceanic and Atmospheric Administration) GOES (Geostationary Operational Environmental Satellite) image to detect the eruption cloud occurred at 0745 h; previous images (0715 h) show no unusual cloud formation.

At about 0800 h, witnesses reported that the eruptive column had become more forceful, now reaching 5-6 km above the cone and beginning to drift to the southwest. Photographs taken at 0759 h from the same camp suggest that small 'nuee ardente' flows may have been descending the south and east flanks of the cone. Photographs taken at 0803 h from the closest town of Reventador, 15 km northeast of the volcano, showed that the eruption column had reached about 7,300 m above the cone and consisted mainly of steam with only a limited ash content. Successive explosions and a constant roar were heard at the construction camp, but not at the town. The 0815 h NOAA GOES image showed the eruption cloud beginning to travel to the southwest.

PAROXYSMAL STAGE

The climactic eruption began at 0912 h and lasted about 45 minutes. It largely destroyed the summit and crater of the cone, leaving deep notches on the NNW and SSW sides of the summit where the crater had been. Eyewitnesses reported that more rocks were being thrown out at this time. During the first minutes of this stage, at least, 5 significant andesitic pyroclastic flows (PF) were produced; their distribution around the cone suggests that they originated at the crater or slightly above it. A photographic sequence taken by R. Saca shows pyroclastic flows descending the southern side of the caldera and obliquely overriding the 200 to 400 m high southern caldera wall (Fig. 3A, B, C, D).

FIG. 3. Sequential series of photographs of the principal pyroclastic flow taken from Reventador town by Roberto Saca. **A.** Note main eruption column above cone at extreme right of photograph, while ash cloud surge forms a secondary column. Also note that the flow is traveling down the south side of the caldera and up onto its southern rim; **B** and **D.** Sequence continues with pyroclastic flow descending rapidly into the Coca river valley. Note the rapid dispersion of ash into the atmosphere; **C.** Photograph of advancing flow taken from the construction camp, 8 km from the cone, which bypassed the camp by going to the left. Photograph taken at approximately the same time as photograph B.

The initial pyroclastic flows were pumice-poor, lithic-rich flows that traveled ESE out of the breached caldera and down steep slopes to reach the Coca river. In doing so, they crossed the principal oil and gas pipelines, destroying the new, empty oil pipeline and carrying away small bridges on the main gravel highway leading to the oilfields. Another one meter diameter pipeline filled with crude oil under pressure did not break, but was displaced ~100 m downslope from its path. This was the closest that the pyroclastic flows came to human activities. No casualties were reported. One small house and 20 head of cattle were buried by the pyroclastic flow. These flows covered approximately 12 km^2, chiefly in the caldera, and had a total bulk volume of about 55 million m^3.

The eruption generated a steam and ash column that rose to 16-17 km (Fig. 4). The lower segment of the eruption column, below 16 km, drifted to the WSW and southwest toward Quito and the populated Interandean Valley at a velocity of 30-45 km/hr. The ash cloud that rose above 16 km traveled to the east and reached southern Colombia and northwestern Brasil.

By midday the ash cloud began to invade the Interandean Valley, progressively darkening the sky. Light gray, silt-size ash began falling in different areas of the Valley between 1300 and 1600 h. Quito's International Airport closed officially at 1245 h. Almost total obscurity had reached Quito and its suburbs by late afternoon, ~100 km from the volcano, leaving a 1-5 mm thick layer of fine ash everywhere. Some towns (*e.g.,* Oyacachi) closer to the volcano received up to 3 cm of ash. It is estimated that approximately 300 million m^3 of ash (bulk volume) were expulsed (LePennec *et al.,* 2003). Residents of Quito and the Valley complained about the strong odor of both SO_2 and H_2S gas. Several deaths and many injuries were attributed to roof cleaning.

SUBSEQUENT ACTIVITY

Other important pulses of the eruption occurred at 1415, 1615-1715 h, and 2005-0100 h on November 3. On November 4 milder explosions occurred between 1200-1300 h. At 1300 h an important explosion took place; IG (Instituto Geofísico) scientists working in the field reported seeing, at least, two pyroclastic flows descending the cone and flowing through the caldera. Possibly, these explosions generated the numerous pumice-rich pyroclastic flows, some of which were large enough to reach the highway, 9 km away. These flows postdate and overlie the slightly older lithic-rich pyroclastic flow deposits (Fig. 5). Small explosions continued on November 5. Debris flows were generated by frequent rains on November 3 and in the following days; they overran and covered parts of the PF deposits and readily reached the Coca River (Mothes *et al.,* 2003). During November 6-7 the volcano continued to emit ash, gases, and steam, but at reduced levels. Explosions terminated between November 7-10.

The first lava flow surfaced on November 6 which was confirmed by distant photographs taken on that day and later by NOAA thermal images taken at 1900 h on November 7. The blocky lava flow originated in the newly formed crater, des-

FIG. 4. Eruption column at 0912 h, reaching 16-17 km high, viewed from Lago Agrio, 90 km to the east. Note the light-colored steam-rich column. Pyroclastic flows just beginning to form at base of the column.

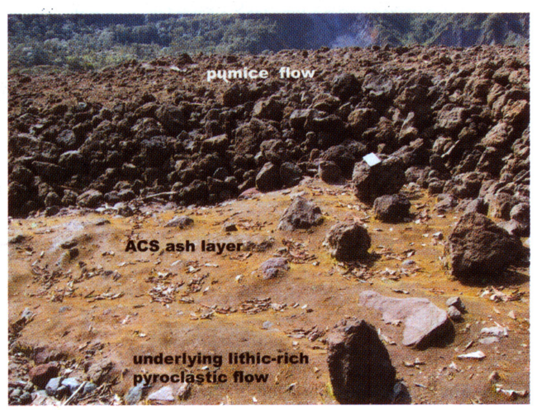

FIG. 5. Photograph taken near the Coca river showing the stratigraphic relations of the pumice pyroclastic flow and the underlying 10 cm thick ash cloud surge (ACS) layer that covers the lithic block-rich initial pyroclastic flow.

cended the southeast side of the cone, and attained a width of several hundred meters and a thickness of ~15 m. From there, it traveled southeastward down the caldera floor near the southern caldera wall. A November 8 overflight by Jorge Anhalzer visually confirmed a 4 km long lava flow, overriding the PF and lahar deposits. By December 3 it had traveled 5 km but was advancing at only ~1-3 m/day. In late December, observers at a distance thought that the lava had all but stopped.

Between November 9 and 21 the short eruption column was continuous, but with increasingly more steam and gas relative to ash. No discrete explosions were heard. Variable debris flow activity occurred, depending upon the intensity of the local rainfall. Occasionally sulfur gases were noted in the Interandean Valley and in Quito.

On November 21 a second blocky lava flow broke out on the lower southeast flank of the cone at ~2,600 m elevation and descended to the ESE. By December 3 it had traveled 2 km and was accumulating up against the side of the first lava flow. The total volume of both lava flows is approximately 36 million m^3.

By December 3, there was no additional explosive or PF activity. The steam-rich plume was now rising to only 1-2 km. The two lava flows continued to move downslope, but only at a few meters/day. Debris flows remained a daily threat to the workers repairing the pipelines and travelers along the main highway.

In conclusion, this Reventador eruption was a very short-lived, violent event. The total bulk volume of erupted material (tephra, lava, and pyroclastic flows) was approximately 0.37 km^3. Based upon the bulk volume of tephra ejected, the eruption qualifies as a small VEI 4 event. It is one of the largest explosive eruptions of an Ecuadorian volcano in the past two centuries.

SEISMIC ACTIVITY

In April 2002, just months prior to the eruption, the IG had fortuitously installed two new seismic stations (1 Hz, vertical, telemetered) that were located at 15 km to the ENE and at 24 km to the southwest of Reventador. After November 3, two additional stations of similar character were installed, one at 7.5 km to the southeast and the other at 8 km to the east of the crater. Other stations that were also important in monitoring the eruption include the two Cayambe stations, located ~40 km to the northwest of Reventador volcano, which due to their signals were recorded on paper drums, produced the most complete seismic record of the precursory activity and the eruption. All of these stations were operating during the November 2002 crisis. Most located earthquakes had shallow hypocenters beneath either the caldera's outer western flanks or under the young cone.

Figure 6 is a histogram showing the daily number of all seismic events detected in November 2002. Prior to the eruption, the region around the volcano averaged 7 events per day. During the eruption, the average stood at 142 events per day. The seismic episode began at 0200 h on November 3 with low-frequency tremor (0.7-1.0 Hz), followed one hour later by a series of almost 200 VT, hybrid, and LP events that accompanied the continuous tremor. The swarm included volcano-tectonic events (at 2-4 Hz, and 12-14 Hz), hybrid events (initial phases at 2-8 Hz followed by main phases at 1-2 Hz), and possibly LP events (1.5-1.7 Hz). It lasted until the main eruption (0912 h) and subsequently decreased, however the seismic tremor continued during the subsequent days. VT and hybrid events continued, apparently associated in time with the emission of the first lava flow.

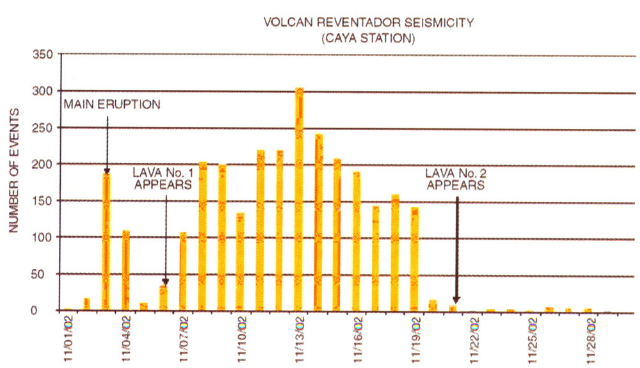

FIG. 6. Graph of the number of seismic events (mainly VT and hybrid types) registered between November 1 and December 1, 2002 at CAYA station, 40 km northwest of Reventador volcano. The almost 200 events labeled 'main eruption' correspond to those earth quakes that preceded the 0912 h eruption.

TOMS SO_2 MEASUREMENTS

On November 3, the NASA Total Ozone Mapping Spectrometer (TOMS) measured 60,000 metric tons of SO_2 in its midday pass, a few hours after the climactic eruption. Subsequently, through November 25 the SO_2 estimates ranged from 5,000 to 30,000 metric tons on a daily basis (Fig. 7), implying a minimum total mass of 260 kilotons. Such important volumes may suggest the presence of a large magma body.

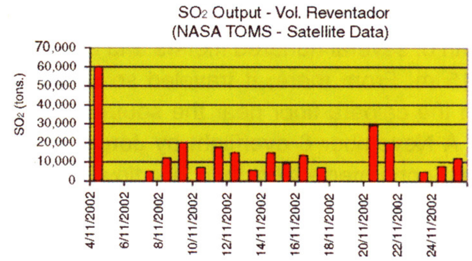

FIG. 7. Graph of Reventador's SO_2 output taken from the NASA TOMS satellite data between November 4-26, 2002. Courtesy of Simon Carn and Arlin Krueger, NASA.

DISCUSSION

The November 3, 2002 eruption of Reventador volcano is notable for its sudden, rapid onset, the brief and limited precursory activity, the apparent efficiency in emptying the volatile-bearing components of the feeding conduit in a few days, as well as for the rapid drop off and the ensuing very low level of both explosive and seismic activity in the days and weeks following November 3. It is of interest to discuss what factors might have played a role in producing this rapid, short-lived, but explosive eruptive event.

One factor might be that the magma had easy access to the surface. The eastern thrust fault belt that defines the eastern foot of the Andes is located 12-15 km to the west of the volcano. The belt consists of many NNE-trending transpressive faults of significant length that are presently inactive or locked up, however a M= 6.9 quake occurred in this belt, 20 km to the northwest of the volcano on March 5, 1987. This fault belt would be a likely area for magma to penetrate and reach the surface, however nowhere has volcanism made its appearance along identified faults in the entire region. The magma conduit that fed the November 3 eruption appears to be located in the same position as that of all historic eruptions, and probably that of the older edifice as well. Clearly, magma ascent is following a well-developed and utilized path to the surface, that is not necessarily related to the fault belt. However, it is of interest that a small north-south lineament appears to bisect the cone.

Reventador volcano had been in a repose cycle for the past 26 years, during which the only activity had been a few permanent steam fumaroles in the crater. Very heavy rainfall (4-6 m/yr) characterizes the region and essentially maintains the caldera saturated in water; consequently the ascent of a heat source to shallow depths should be readily signaled by increased steam emission. For several months prior to the January 5, 1976 eruption, a steam column of 1-2 km height was observed constantly, apparently due to the new magma ascending the conduit and attaining shallow depths. The fact that there was no change in the fumarolic activity in the crater two weeks before the 2002 eruption probably implies that the magma was still at considerable depth. Alternatively, the magma might have quietly ascended the conduit and dried out the central core of the cone, however at some point increased steam emission should have been noticed.

Workers at the camp, only 8 km from the cone, had a good view of the cone, weather permitting, and had not noticed a steam column on the cone in the days preceding the eruption. However, they did see an energetic steam column at daybreak on November 3. With the onset of the eruption, steam generation became continuous, which suggests that the cone had not dried out beforehand and that only a heat source was lacking to produce steaming. Consequently, it would seem that the magma must have ascended the conduit very rapidly, probably from depths of <10 km, and only came in contact with groundwater in the early morning hours of November 3. The lack of reaction rims on amphibole phenocrysts also implies a very fast ascent rate (Hall *et al.,* 2003). Furthermore, it is concluded that the six hours of VT and hybrid seismic activity between 0300 and 0900 h of November 3 probably corresponds to the period of the rapid ascent of the gases and magma.

The beginning of the eruption was very explosive. Following several hours of phreatic and phreato-magmatic activity, the main eruption occurred at 0912 h and sent pyroclastic flows racing across the caldera and an eruption column climbing to 17 km. The deposits of these initial flows have a sandy matrix and carry abundant angular clasts up to 5-20 cm and blocks up to 5 m across, comprised mainly of accessory lithic material of varied rock types. Juvenile pumiceous material, while present, is greatly subordinate in volume to the lithic material and is only present as small centimeter-size clasts or as part of the matrix. Given that the cone's summit lost about 49 million m^3 of older material in the initial phase of the 0912 h explosion, clearly the abundant lithic portion of the initial pyroclastic flows was derived from this explosive event. Because vesiculated pumice is not an important component in these deposits, it is surmised that gas-rich magma had not yet arrived in volume in the upper cone.

The violent onset of the eruption was apparently triggered by the sudden depressurization of a pressurized gas-rich phase of the upper conduit at 0912 h. Undoubtedly, a good seal existed in the conduit which led to the high pressurization of the early gases, as well as preventing steam from escaping and giving a warning. Likewise, an accumulated gas phase would be in agreement with the very high SO_2 values that were reported shortly after the eruption. The explosive onset was greatly intensified by steam derived by the magmatic heating of groundwater, as also suggested by the light-colored, apparently steam-rich, eruption column (Fig. 4). Steam as an important component is also suggested by the fact that the ash generated in the early phase of the eruption and that fell over much of the Interandean Valley is very fine-grained and whitish gray in color, suggesting a phreato-magmatic origin. Scoria or vesiculated grains were not observed. The depressurization also resulted in the rapid ascent (~1000m/min) to 17 km of the gas-rich eruption column.

The pumice-rich pyroclastic flows are thought to have been generated on November 4, apparently related to the large explosion that occurred at 1300 h. These flows could not have immediately followed the 0912 h November 3 event, since there had to have been an interval of time in which the fine-grained ash of the ash cloud surge (ACS) that accompanied the initial pyroclastic flow (Fig. 3) could have settled out to form the uniformily thick, well-sorted ash layer that is observed everywhere, as well as to have had time to compact itself appreciably, probably by rainfall. Photographs taken in the late afternoon of November 3 show that fine ash was still falling in the caldera. Furthermore, debris flow activity on November 3-4 left numerous lahar deposits upon the basal pyroclastic flow deposits as well as upon the ACS ash layer. The pumice flows invariably overlie either the ACS ash layer or the lahar deposits and show no sign of having disturbed them (Fig. 5). Thus, it would seem that the pumice flows followed the main eruption by a day or so. This, in turn, implies that gas-rich magma was still available in the conduit at least until November 4, although by November 6 the magma was relatively degassed and forming lava flows.

The brief and limited precursory activity prior to the eruption is baffling. As mentioned earlier, there was no obvious steaming or other visual manifestation of pending activity prior to the eruption. Although the operative seismic net was not ideal, it nevertheless monitored very well the October 6 seismic swarm, as well as the seismicity of November 3. And yet there was no ramping up of seismic activity in the four weeks prior to the eruption.

Why didn't the ascending magma generate a seismic warning in the days and weeks prior to the sudden eruption? A very fluid magma, a deep source, and a fast ascent of the magma are all conceivable explanations. Theoretically, magma can move aseismically, especially when it has favorable properties, such as low viscosity, low crystal contents, and abundant volatiles in solution. That the Reventador volcano magma was relatively fluid and mobile is suggested by the nature of the eruption, despite the fact that the SiO_2 contents of the lavas are not low (58-59%) and the percentage of crystals in the glassy matrix is moderate (~20%). The magma source was apparently not so deep, as suggested by the 10-11 km deep hypocenters of the October 6 swarm, nor so shallow as to generate steam. Because no additional seismicity was detected under the volcano between October 6 and November 3, it is thought that the magma was either relatively fluid and flowed aseismically, without generation of VT or hybrid quakes, or conversely it was quiet and immobile until the final, rapid ascent to the surface was initiated. Previously, it was suggested that the magma ascent rate was rapid and probably preceded by an abundance of volatiles, both of magmatic and meteoric origin. In addition, the rapid ascent of the magma would delay the release of its volatiles until high in the edifice, which would also contribute to the explosiveness of the November 3 onset.

The short-lived nature of the eruptive event is perhaps due to the fact that most of the ex-solved gases had collected in the higher parts of the conduit and were expelled during the first days. Subsequently, on November 6 the quiet effusive stage of relatively degassed magma began, while the final explosive activity was ending. Increasing viscosity of the degassing magma or closure of the feeding conduit once the gas and magma pressures had decreased may have also aided in finishing the cycle. Given the frequency of eruptions of Reventador volcano during the XX century, it is clear that magma is readily available at depth. Consequently, it is not realistic to exclude the possibility of renewed volcanic activity in the near future.

Finally, it is important to conclude that for those volcanoes that are characterized by low silica, gas-rich, fluid magmas, magma ascent can be relatively aseismic, rapid, and give little warning. In the case of Reventador volcano, only a telemetered seismic station operating directly on the cone might have provided some warning of the impending eruption.

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