Catastrophic Volcanic Collapse: Relation to Hydrothermal Processes

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Catastrophic volcanic collapse, without precursory magmatic activity, is characteristic of many volcanic disasters. The extent and locations of hydrothermal discharges at Nevado del Ruiz volcano, Colombia, suggest that at many volcanoes collapse may result from the interactions between hydrothermal fluids and the volcanic edifice. Rock dissolution and hydrothermal mineral alteration, combined with physical triggers such as earthquakes, can produce volcanic collapse. Hot spring water compositions, residence times, and flow paths through faults were used to model potential collapse at Ruiz. Caldera dimensions, deposits, and alteration mineral volumes are consistent with parameters observed at other volcanoes.

Catastrophic collapse is a severe hazard at strato volcanoes [for example, Mount St. Helens (*1*) and Mount St. Augustine (*2*)] and shield volcanoes [for example, Hawaii (*3*)]. In Indonesia, most volcanoes of an elevation greater than 2000 m have had edifice collapse (*4*). Some of the most famous collapses (for example, at Bandaisan, Japan) are puzzling because there was no clear evidence of precursory or postcollapse volcanic activity (*5*). The "Bandai-type" eruptions (*5*), considered to be solely phreatic (*6*), emit no juvenile material. In "Bezymianny-type" eruptions like Mount St. Helens (*2*), slope failure permits eruption of magma and produces explosive lateral blasts. Mass flows and associated lateral blasts travel 50 to 100 km, affect 500 to 1500 km^2, and move as fast as 100 m s^{-1} (*2*). Volcanic debris avalanches have occurred globally on average four times each century during the last 500 years (*7*), with at least six examples this century (*2*). Geothermal systems (*8*) develop in many volcanoes by the interaction of magmatic gases with groundwater (*9–11*) and produce extensive rock dissolution and hydrothermal mineral alteration that might lead to the gravitational instability of the volcanic edifice. These zones should be studied and monitored carefully, and the hazards of possible volcanic collapse and potential lateral blast should be assessed. This is important for volcanoes located in densely populated areas such as Japan, Indonesia, and Latin America. In this report, we evaluate this on the basis of analysis of Nevado del Ruiz volcano, Colombia (*12*), and other volcanoes (*13, 14*).

Ruiz chloride and sulfate concentrations, sulfur isotopes (*15*), and oxygen and deuterium isotopes (*10*) suggest a magmatic input to acid sulfate waters that discharge at many locations (Fig. 1). Saline acid sulfate waters have compositions similar to the dissolution of 10 g of Ruiz pyroclastic rock per kilogram of water (*12*). Acid sulfate waters (Fig. 1) are discharged along the Villamaría-Termales fault [a seismically active regional fault (*16*)] and the Palestina fault (controls vent locations in the volcanic chain). Neutral chloride waters occur on the western and southeastern slopes of the volcano, whereas bicarbonate waters (Fig. 1) are more widespread. Most hot springs are also located near the contact between the relatively impermeable basement rocks and young volcanic pile.

The compositional variation of the Ruiz waters suggests that they are controlled by rock (*17*) dissolution (Fig. 2A). Figure 2B shows the rock dissolution lines for average basalt, crustal rock, and granite (*18*) together with the composition of different hydrothermal systems (*12*). Acid sulfate waters fall on or close to rock dissolution lines. Bicarbonate and neutral chloride waters also fall close to those lines. However, for those waters and pH conditions, the more relevant lines are equilibrium boundaries for the mineral pairs calcite-dolomite and K-feldspar–albite (*13*). Reactions between crater gases (sampled 1 day before the 13 November 1985 eruption) and basaltic andesite from Ruiz were simulated (*13, 19, 20*). These gas samples contained the largest magmatic component collected at Ruiz, as indicated by the content of sulfur dioxide of magmatic origin (*13*) and the relative proportions of SO_2, CO_2, HCl, and H_2S (*11*). Compositions of Aguas Caliente (AC) water can be closely modeled by reacting 9 g of rock with 1 kg of hydrothermal fluid to produce 6 g of alteration minerals (*12*) [close to the 10 g of rock suggested by earlier work (*13*) that considered only rock dissolution].

The residence time of 15 years for AC waters [7.5 km north-northeast of the El Ruiz crater (Fig. 1)], calculated on tritium data (*10*), implies that the average fluid horizontal velocity near the fault is ≈500 m year^{-1}. Other geochemical data [transients in Cl^- and SO_4^{2-} concentrations (*21*) and He isotopes (*22, 23*)] suggest that rapid gaseous magmatic fluids mix with more slowly moving meteoric fluids to produce

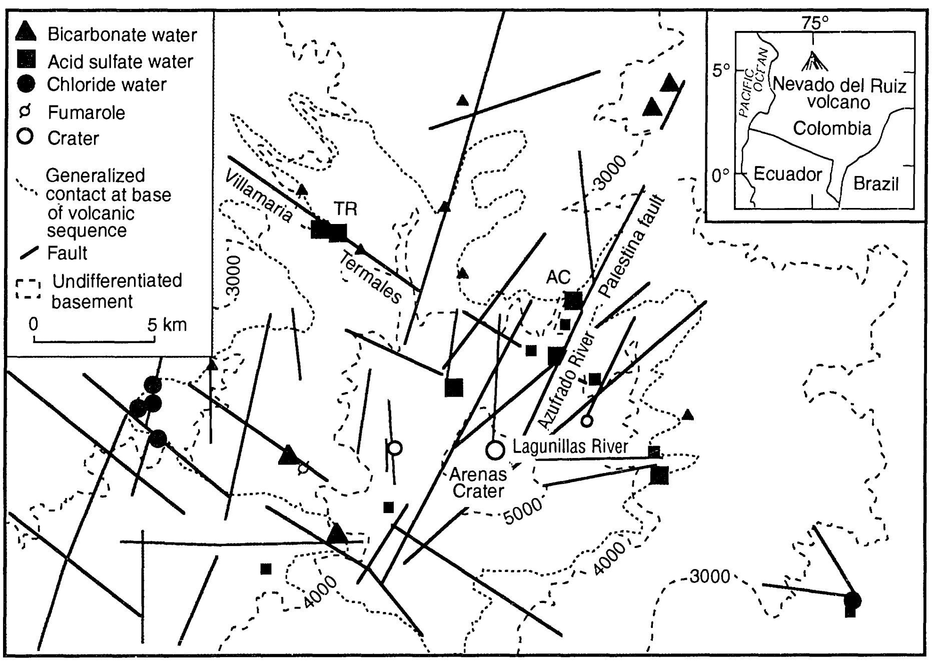

Fig. 1. Nevado del Ruiz volcano and its hydrothermal system. Contours are in meters above sea level. Shown are selected faults, lineaments, and hydrothermal springs as well as generalized contact between the volcanic edifice and underlying basement rocks. Small and large symbols represent waters with total dissolved solids <1000 mg per kilogram of water and >1000 mg per kilogram of water, respectively.

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water compositions similar to that of the AC waters.

Aguas Caliente is located at a relatively high volcanic edifice elevation, which suggests that the fluids follow a shallow path. We assume the fluid moves through a thickness T and average height (700 m) along the fault zone. Mass conservation requires that a volumetric flow (area × velocity) of (3.5×10^5) T cubic meters of fluid annually passes through the slab. For rock density of 2500 kg m^{-3}, the slab mass is (1.33×10^{10}) T kg. We estimate that T equals 10 to 50 m from observations at the hot springs and in the adjacent Azufrado Canyon and calculate, therefore, that ≈4200 years are needed to completely alter the rocks in the slab. These results are limited by the assumptions of the model that (i) the fluid moves at average velocity of 500 m $year^{-1}$ and (ii) every volume of fluid entering the system follows that path and reacts to produce water compositions similar to AC [the almost steady-state composition of those waters supports this (*12*)].

Dissolution in the Palestina fault is calculated to be 12,600 m^3 of rock per year, assuming T is 10 m and 1 kg of fluid alters 9 g of rock. Ruiz data fall between the estimates for Poás (1,650 m^3 of rock per year), a much smaller system (*14*), and for White Island (22,000 m^3 of rock per year) (*13, 24*), where similar processes have been reported.

Volcanic collapse data from around the world (*2*) show that the horseshoe-shaped depressions or calderas commonly have a length between 2 and 7 km (with an equal or less width). Assuming such a volcanic collapse were to occur at Ruiz, we considered that range in our calculations. The alteration zone along the fault is assumed to be 10 to 50 m wide, and alteration products are considered to be uniformly distributed throughout the volume of avalanche products resulting from collapse. From our simulation results, we assume that 6 g of altered materials are produced from each 9 g of original rock. The volume of the deposit is assumed to be equal to the caldera volume (Fig. 3).

A range of possible caldera dimensions, volumes of deposits, and percentages of alteration minerals is expected, given the manner in which volcanic sector collapse causes large blocks of the edifice to become intermixed with fault zone alteration materials, producing the classic volcanic debris avalanche deposit (*25, 26*) (Table 1). The predicted range in contained alteration minerals is between 0.5 to 5.0%, which compares favorably to data from the Mount St. Helens debris avalanche, which contained an average of 1.1% by weight (maximum 3.4%) of clay-sized fraction (*26*). A length of 7 km and width of 5 km might be considered an extreme case for Ruiz because that is roughly the sector defined by the Palestina and Villamaría-Termales faults. If that entire sector were to collapse, a higher percentage would be predicted because it would contain alteration associated with both faults and the basal contact zone. The deposit volumes in Table 1 are consistent with those found around the world (*2*), usually much less than 10 km^3.

Rock dissolution and precipitation of alteration minerals, such as clays, on the basal contacts near fault planes provide low-angle planes on which detachment and mass movement is possible. The inherent gravitational instability of volcanoes, together with the presence of altered, soft rocks, facilitates slope failure, partial collapse of the volcano, and sudden decompression of the hydrothermal and magmatic system. This may trigger explosive lateral blasts of Bezymianny-type eruptions.

Alteration zonation around the hot springs at Ruiz is intense along the Palestina fault plane and contains fine-grained minerals such as clays, quartz, sulfur, pyrite, anhydrite, and alunites (*12*). The Holocene record at Ruiz (*27*) suggests that the deeply dissected troughs and strongly hydrothermally altered north and east flanks, together with the unstable glacial margins, make the summit unstable. External triggers such as earthquakes can initiate gravitational failure and explosive eruptions. Voluminous debris avalanches occurred in the eruptions 3100 years before the present and in A.D. 1595 and 1895 and were found with a horseshoe-shaped amphitheater, 7.5 km by 2.5 km and 1.4 km deep, in the

Table 1. Volume of deposits and percentage of alteration estimated for several possible volcanic collapses at Nevado del Ruiz volcano. L and W, length and width, respectively, of sector that collapses; T, width of the fault zone.

L (km)	W (km)	Volume of deposit (km^3)	Alteration minerals (%) T = 10 m	Alteration minerals (%) T = 50 m
2.00	2.00	0.27	1.0	4.7
4.00	2.00	1.03	1.0	4.9
4.00	4.00	2.12	0.5	2.4
5.00	2.00	1.60	1.0	5.0
5.00	5.00	4.15	0.4	1.9
7.00	5.00	7.90	0.4	2.0

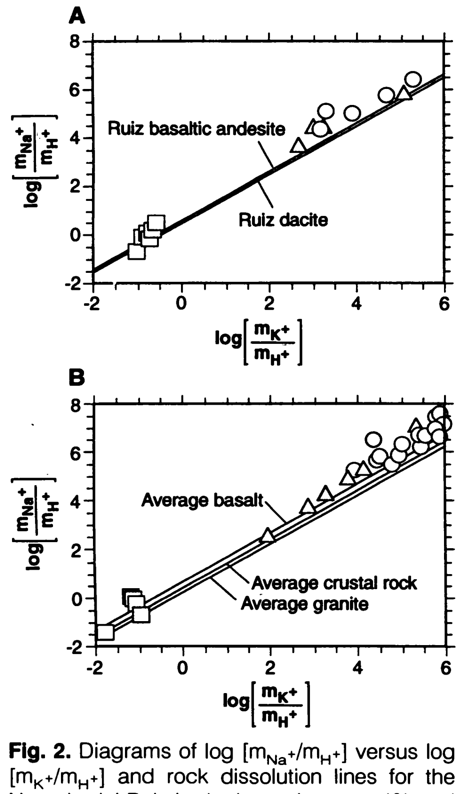

Fig. 2. Diagrams of log [m_{Na^+}/m_{H^+}] versus log [m_{K^+}/m_{H^+}] and rock dissolution lines for the Nevado del Ruiz hydrothermal system (**A**) and other volcanoes of the world (**B**) (*13*). Data for (B) are from (*12*); the composition of Ruiz dacite and Ruiz basaltic andesite is from (*18*); and the composition of average crustal rock, average basalt, and average granite is from (*19*). Acid sulfate waters, circles; bicarbonate waters, triangles; and neutral chloride waters, circles.

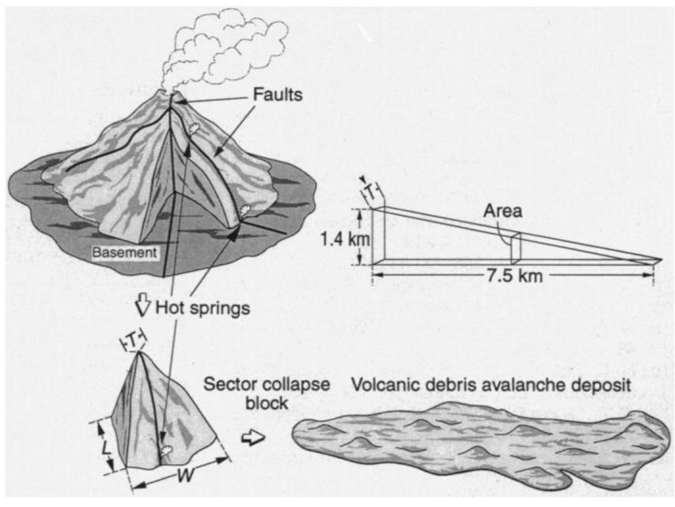

Fig. 3. Conceptual figure of Nevado del Ruiz volcano, showing possible volcanic collapse around the Palestina fault to produce a sector collapse and volcanic debris avalanche deposit. L and W are the length and width of the sector that collapses, and T is the width of the fault zone. The dimensions of the alteration zone used in the model are shown in the upper right, along with the mean area (Area).

Azufrado Canyon headwaters (Palestina fault zone). The missing 26 km^3 is interpreted to represent the cumulative volume of multiple, large rockslide avalanches of hydrothermally altered materials. On the eastern flank, the Lagunillas River canyon contains a similar feature 2.5 km long, 1 km wide, and 200 to 400 m deep. This depression also cuts into highly altered materials but does not show the obvious tectonic control exhibited on the north and northwest slopes. The processes that have been modeled may be partially responsible for recent sector collapse and eruptions at Ruiz.

The model proposed may explain the excess travel distance of volcanic debris avalanches (*28*). For modern examples (*29*) and many ancient deposits (*2, 25*), the ratio of vertical drop (*H*) to travel length (*L*) for volcanic debris avalanches is much lower than the ratio for nonvolcanic deposits of similar volume. Edifice failure, related to the presence of extensive alteration materials, especially clays, along low-angle detachment planes and accompanied by the boiling of supercritical hydrothermal fluids is predicted to produce low-rigidity, perhaps partially fluidized (*29*) avalanches capable of traveling great distances.

Many ore deposits associated with acid sulfate alteration show features that suggest that rapid unroofing of the hydrothermal systems may have played an important role in ore formation (*30*). The presence of healed veins of calcite and anhydrite in ore deposits such as that in Lihir Island (Papua New Guinea) (*31*) corresponds to the brecciation and later deposition caused by the sudden decompression of the hydrothermal system. A large sector collapse apparently occurred so recently at Louise caldera on Lihir Island (*32*) that the debris avalanche deposit is preserved in this hydrothermal system, which is still depositing gold (*32*).

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Interspecific and Intraspecific Horizontal Transfer of *Wolbachia* in *Drosophila*

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Cytoplasmic incompatibility (CI) in *Drosophila simulans* is related to infection of the germ line by a rickettsial endosymbiont (genus *Wolbachia*). *Wolbachia* were transferred by microinjection of egg cytoplasm into uninfected eggs of both *D. simulans* and *D. melanogaster* to generate infected populations. Transinfected strains of *D. melanogaster* with lower densities of *Wolbachia* than the naturally infected *D. simulans* strain did not express high levels of CI. However, transinfected *D. melanogaster* egg cytoplasm, transferred back into *D. simulans*, generated infected populations that expressed CI at levels near those of the naturally infected strain. A transinfected *D. melanogaster* line selected for increased levels of CI expression also displayed increased symbiont densities. These data suggest that a threshold level of infection is required for normal expression of CI and that host factors help determine the density of the symbiont in the host.

Cytoplasmic incompatibility is a developmental defect described in a number of insect species (*1*). It is expressed when males that carry the bacterial endosymbiont *Wolbachia* are mated to females that lack the infection. Such a cross in *Drosophila* produces few, if any, viable offspring (*2*). However, the reciprocal cross—uninfected males mated to infected females—yields normal progeny counts, as do crosses within a given strain of infected individuals.

The nonreciprocal nature of CI indicates that the male's contribution is critical to CI expression. However, *Wolbachia* are not present in mature sperm; paternal transmission occurs only rarely, if at all (*3*). The microorganism in the adult male somehow renders the sperm incapable of successfully completing fertilization after entry into an uninfected egg cytoplasm (*4, 5*). Compatible crosses involving infected females produce normal progeny counts regardless of the infection state of the male. Therefore, eggs derived from infected females somehow negate or rescue the action of *Wolbachia* on sperm.

Studies of CI have been hampered by the difficulty in culturing the symbiont outside of its host. To gain insight into the cellular and molecular basis of CI, we transinfected *Wolbachia* into uninfected *D. simulans* and *D. melanogaster* hosts and monitored their cellular distributions and CI expression with confocal microscopy and

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