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Volcán Reventador's unusual umbrella

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[1] Photographs of a volcanic column in a recent eruption of Reventador show a prominently scalloped umbrella that is unlike any umbrella previously documented on a volcanic column. We propose that the scallops in this umbrella are the result of a *turbulent* Rayleigh–Taylor (RT) instability, a type of fluid instability with no precedents in volcanology. Negative buoyancy drives this instability, and we ascribe the unusual negative buoyancy of the Reventador umbrella to the fact that the Reventador column fed on a cool co-ignimbrite cloud. From the wavelength of the scallops, we estimate a value for the eddy viscosity of the umbrella, $\nu_d \approx 4{,}000$ m^2/s, the first such value to be inferred directly from an observation in the field. Collapse of the umbrella back to the ground could result in a previously unrecognized hazardous flow. We hope this work will elicit new reports on scalloped umbrellas and further study of the characteristics and evolution of such umbrellas.

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1. Introduction

[2] Volcán Reventador (Spanish for "One that Explodes"), 100 km from Quito, Ecuador, erupted cataclysmically at 9:12 a.m. local time on November 3, 2002, following seven hours of seismic activity and a steam phase. The eruption sent a towering Plinian column 17 km into the stratosphere (Figure 1) and a pyroclastic flow 9 km down valleys [*Hall et al.*, 2004]. The pyroclastic flow caused severe damage to principal petroleum pipelines; the attendant co-ignimbrite clouds and the columns that fed on them provided sufficient ash to close the Quito airport for 10 days. One of these columns displayed an unusual, scalloped umbrella (Figure 2). Scalloped umbrellas have not previously been reported in the volcanology literature to our knowledge, and a search of several hundred images on the WWW and in the literature revealed only one other plausible candidate, the plume from the 8:41 a.m. eruption on June 13, 1992 (see http://pubs.usgs.gov/pinatubo/hoblitt2/fig15.jpg).

[3] A co-ignimbrite cloud forms from ash and gas rising buoyantly from the top of a descending pyroclastic flow [*Sparks and Walker*, 1977]. A co-ignimbrite cloud can be sheared back toward the center of the eruption and may comingle with directly ascending material [*Baxter et al.*, 1998]. In the case of Reventador, the co-ignimbrite cloud hovered at lower elevation than the rapidly ascending, white buoyant cloud that may be seen rising from the vent in the background of Figure 2b.

[4] The usual volcanic column (Figures 1 and 3a) as well as the usual nuclear-test column (Figure 3b) consists of a stalk capped with an umbrella. The umbrella forms when the fluid in the stalk reaches neutral buoyancy, possibly with some overshooting in the center of the rising column (Figure 3c). The outer shape of the umbrella reflects a toroidal circulation (Figure 3d) that draws ambient air in from the atmosphere at the bottom of the stalk and forces mixing of the ambient air with hotter, less dense fluid inside the ascending stalk [*Glasstone and Dolan*, 1977]. In most cases, the surface of the umbrella develops a "knuckled" or "cauliflowered" texture (Figure 3).

[5] In contrast, on the Reventador column of Figure 2 the umbrella was scalloped orthogonal to the plane of the toroidal circulation. Dimensions are difficult to ascertain from the eyewitness photos available to us, but the photograph of Figure 2c allows for rough measurements (for details refer to auxiliary material[1]). On the basis of these measurements, we estimate the diameter of the umbrella as ≈3.5 km (perhaps 3.5 ± 2.5 km), its half circumference as ≈5.5 km, and 8 scallops per half circumference, giving a scallop wavelength of about 0.7 km (perhaps 0.7 ± 0.5 km). Further, we estimate the thickness of the umbrella as ≈0.9 km, the diameter of the stalk as ≈1 km, and the amplitude of the scallops as several hundred meters. The explanation proposed here is not affected by the likely uncertainties in these quantities.

2. Hypothesis

[6] The RT instability [*Taylor*, 1950; *Sharp*, 1984] occurs on the bottom surface of a layer of denser fluid that tops a layer of lighter fluid in the presence of a gravitational field. In the *classic* RT instability, both fluids are initially at rest, and, therefore, the instability is governed by the molecular viscosity (i.e., the usual viscosity). The classic RT instability has precedents in volcanology [*Colgate and Sigurgeirsson*, 1973; *Wohletz*, 1986]. In the *turbulent* RT instability of interest here, the fluid in the upper layer is *already turbulent at the onset of the instability*, and, therefore, the instability is governed by the eddy viscosity [*Tennekes and Lumley*, 1972]. The turbulent RT instability has precedents in meteorology [*Agee*, 1975] and perhaps in other sciences, but none in volcanology.

[7] We ascribe the scalloped structure of the Reventador umbrella to the occurrence of a turbulent RT instability on the bottom surface of the umbrella. The instability occurs along the outer rim of the umbrella if the ashy suspension there is denser than the ambient air under the umbrella. We

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Figure 1. The larger Reventador volcanic column at 9:12 a.m. November 03, 2002, reaching 16–17 km high, viewed from Lago Agrio, 90 km to the east of the eruption site on which this column grew. Photographer unknown. Note the light-colored, steam-rich column.

present an analysis showing that the conditions necessary for such an instability are consistent with those likely in the Reventador column, given the geologic conditions of the eruption.

3. Analysis and Assumptions

[8] The RT instability may occur at all wavelengths. Nevertheless, the rate of growth of the instability is maximum for a wavelength [*Chandrasekhar*, 1981]

$$\lambda = 4\pi\left(\frac{\nu^2\alpha}{g}\right)^{1/3}, \tag{1}$$

where $\nu \equiv (\mu_d + \mu_l)/(\rho_d + \rho_l)$, $\alpha \equiv (\rho_d - \rho_l)/(\rho_d + \rho_l)$, μ_d is the viscosity of the denser fluid, μ_l is the viscosity of the lighter fluid, ρ_d is the density of the denser fluid, ρ_l is the density of the lighter fluid, and g is the gravitational acceleration. The characteristic time associated with the wavelength of (1) is

$$\tau = \left(\frac{\nu}{g^2\alpha}\right)^{1/3} \tag{2}$$

and represents the time required for the RT instability to become manifest.

[9] (To grasp the physics of the RT instability, imagine that the initially horizontal interface between the fluids ($y = 0$ for all x) becomes sinusoidal, so that $y = a \sin(2\pi x/\lambda)$ and $\dot{y} = \dot{a} \sin(2\pi x/\lambda)$, where a is the amplitude of the instability and $\dot{a}$ its rate of growth. A sinusoidal interface implies that lighter fluid moves up and denser fluid moves down, and therefore that the gravitational field *yields* energy. Now this energy is partly dissipated viscously and partly transformed into kinetic energy; by studying the associated equation of conservation of energy, it is possible to show that $\dot{a}$ is maximum for a specific wavelength λ—the wavelength given by (1).)

[10] In the case of interest here, we assume that μ_d (i.e., the viscosity of the umbrella) is much larger than μ_l (i.e., the viscosity of the ambient air). In addition, we assume that along its outer rim the umbrella is slightly denser than the ambient air, and write $\Delta\rho \equiv \rho_d - \rho_l$ and $\rho_d + \rho_l \approx 2\rho_d$. With these assumptions we have $\nu \approx \mu_d/(2\rho_d) = \nu_d/2$, where ν_d is the kinematic viscosity of the umbrella, and $\alpha \approx \Delta\rho/(2\rho_d)$, and (1) and (2) become

$$\lambda \approx 2\pi\frac{\nu_d^{2/3}}{g^{1/3}}\left(\frac{\Delta\rho}{\rho_d}\right)^{1/3} \quad \text{and} \quad \tau \approx \frac{\nu_d^{1/3}}{g^{2/3}}\left(\frac{\Delta\rho}{\rho_d}\right)^{-1/3}. \tag{3}$$

[11] Now we consider the quantity $(\Delta\rho/\rho_d)^{1/3}$ that appears in (3). A positive value of $\Delta\rho/\rho_d$ signifies that the outer rim of the umbrella is negatively buoyant. As a result of the cubic root, even a modest value of $\Delta\rho/\rho_d$ leads to a value of $(\Delta\rho/\rho_d)^{1/3}$ of order 1. (For example, $\Delta\rho/\rho_d = 0.1$ leads to $(\Delta\rho/\rho_d)^{1/3} \approx 0.5$.) Nevertheless, the outer rim of the umbrella must be negatively buoyant, at least to a small degree, or there would be no driving force to propel the RT instability. With this assumption in place, we can set $(\Delta\rho/\rho_d)^{1/3} \approx 1$ in (3).

[12] Next we consider the kinematic viscosity ν_d in the context of a turbulent RT instability. If the umbrella is turbulent, it is populated by turbulent eddies in a vast range of lengthscales. These turbulent eddies can effect momentum transfer and therefore endow the umbrella with an eddy viscosity [*Tennekes and Lumley*, 1972]. The largest turbulent eddies have a size comparable with the thickness h of the umbrella and can be identified with the toroidal circulation of Figure 3d. These eddies dominate the momentum transfer and therefore the eddy viscosity [*Landau and Lifshitz*, 2000]. If we denote the characteristic velocity of the largest eddies by u, we can estimate the eddy viscosity as $\nu_d \approx uh$ [*Landau and Lifshitz*, 2000], the dominant wavelength as $\lambda \approx 2\pi(uh)^{2/3}/g^{1/3}$, and the characteristic time as $\tau \approx (uh)^{1/3}/g^{2/3}$.

[13] (To visualize the origin of the eddy viscosity, imagine a vertical plane bisecting the umbrella and one side of the plane being sheared downwards with respect to the opposite side; this is the sort of shearing required to form scallops. Then, the turbulent eddies provide currents orthogonal to the plane, thereby "sewing" the two sides of the plane together. Thus the eddies resist the shearing motion, much as a stitch prevents two pieces of cloth from sliding relative to one another. The molecular viscosity works in a similar way [*Tennekes and Lumley*, 1972], only that the currents normal to the plane are diffusive currents, and therefore much weaker than the currents provided by the turbulent eddies—unless there is no turbulence, in which case the molecular viscosity is the only available viscosity.)

4. Results

[14] To obtain $\lambda \approx 0.7$ km (the wavelength observed in the Reventador umbrella) we must have an eddy viscosity of about 4,000 $\mathrm{m^2/s}$. The attendant velocity of the largest turbulent eddies is $u \approx 5$ m/s (for $h \approx 0.9$ km). The characteristic time is $\tau \approx 5$ s.

[15] The estimated value of the eddy viscosity is quite large. For comparison, the molecular viscosity of water is 10^9 times smaller. It is apparent that any feasible molecular viscosity could only give a wavelength orders of magnitude smaller than the observed wavelength. We conclude that the relevant viscosity cannot be the molecular viscosity: to account for the observed wavelengths, there must be turbulence, fast turbulent eddies, and the attendant eddy viscosity. K. H. Wohletz (personal communication, 2005) estimated

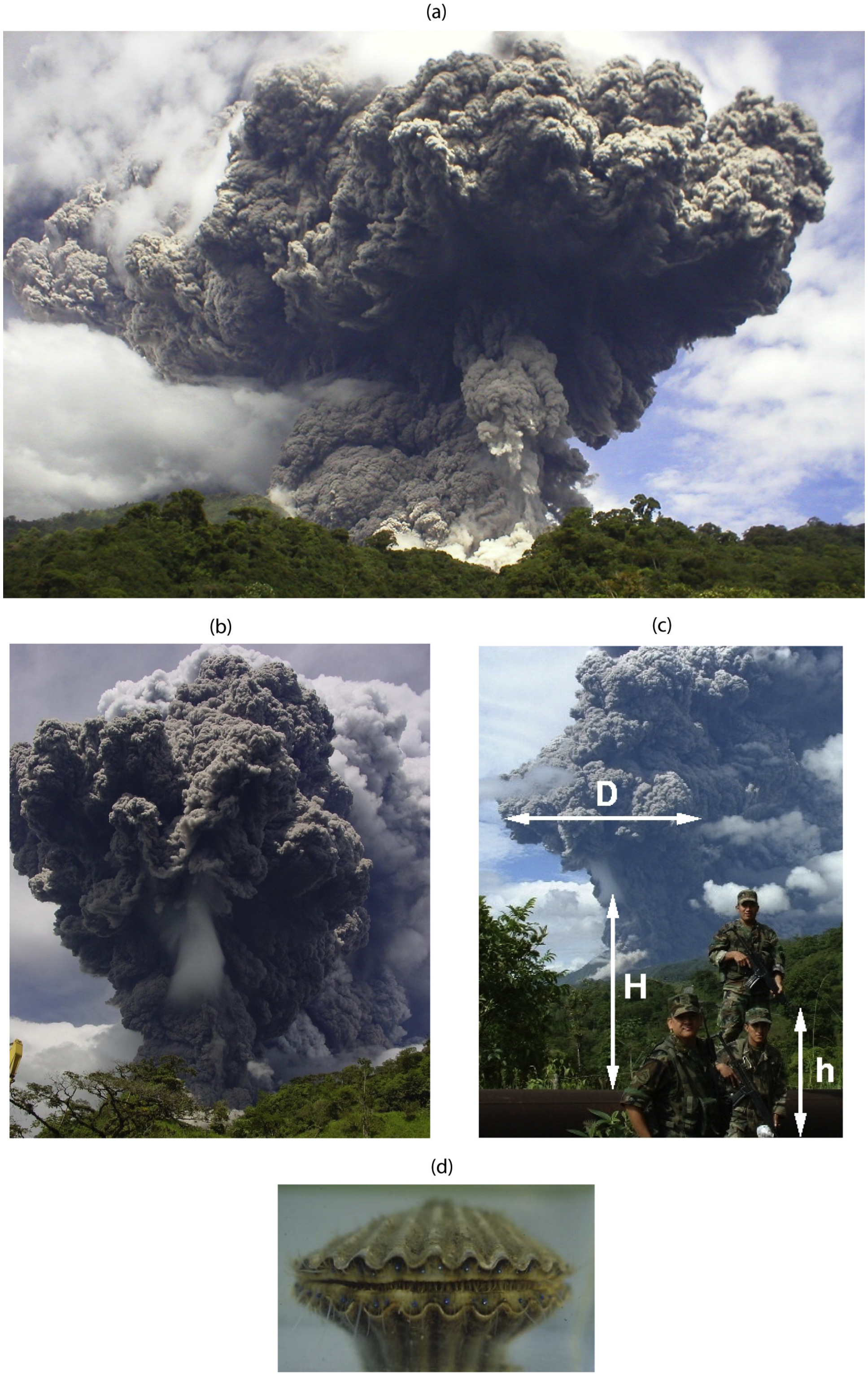

Figure 2. Reventador co-ignimbrite column with scalloped umbrella. The co-ignimbrite cloud on which this column fed was just forming at the base of the larger column of Figure 1. (a) Photograph by Armando Alvarez Sánchez, Cruz Roja Ecuatoriana. (b) Photograph courtesy of Techint Co., taken from a construction camp approximately 8 km from the erupting cone. (c) Photograph courtesy of Techint Co. We use the segments marked *D*, *H* and *h* to perform measurements (refer to auxiliary material). (d) Scallop (a marine bivalve of distinctive shell). Photographer unknown.

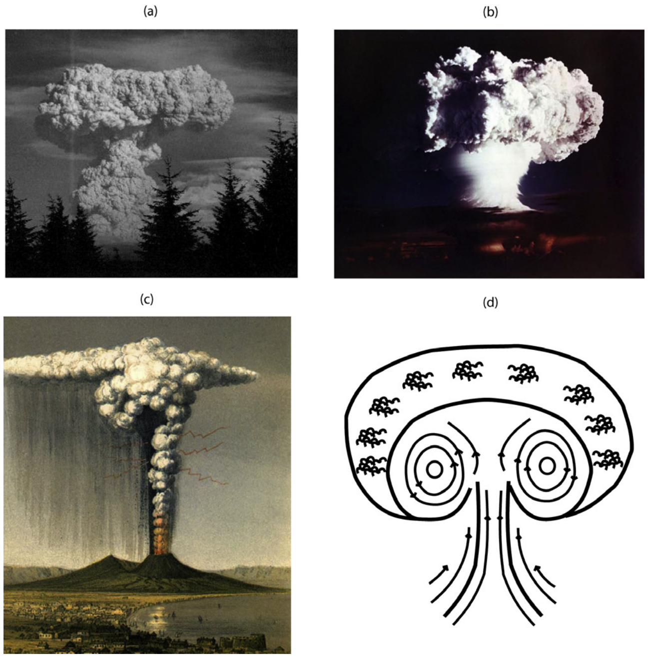

Figure 3. (a) Plinian volcanic column over Mount St. Helens. Photographer unknown. (b) Nuclear-test column, Ivy-Mike, 1952. Photograph U.S. Government. Photographer unknown. (c) Classical lithograph titled “The Eruption of Vesuvius as Seen from Naples, October 1822.” (d) Toroidal circulation. Adapted from *Glasstone and Dolan* [1977].

an eddy velocity of $\approx$10 m/s for a Plinian column at Mount St. Helens and used equation (5) of *Valentine and Wohletz* [1989] to obtain a lower bound for the eddy viscosity of 200 m^2/s. This lower bound is consistent with our estimated value of the eddy viscosity.

5. Implications for Volcanic Column Dynamics and Hazards

[16] From the previous section, we conclude that scallops of a wavelength comparable with the wavelength of the Reventador umbrella can form in a suitably short time if the largest eddies in the umbrella are sufficiently fast, with a characteristic velocity of several meters per second. Note that the characteristic velocity of the largest eddies scales with the turbulent power per unit mass, i.e., with the rate of production of turbulent energy per unit mass, denoted by ϵ, in the form $u \sim (h\epsilon)^{1/3}$ [*Landau and Lifshitz*, 2000]. Volcanic columns are invariably very turbulent and can, in principle, develop scalloped umbrellas as prominent as Reventador’s. Yet most volcanic columns do not develop scalloped umbrellas (e.g., Figures 3a and 3c), because in most volcanic columns the outer rim of the umbrella remains neutrally buoyant. In fact, if the fluid rising in the stalk is superheated steam, or if the particle loading is light, or if the entrained particles are hot and transmit heat to the vapor phase, for example, then the umbrella can undergo an extensive lateral expansion while its outer rim remains neutrally buoyant. (A common example is afforded by a meteorological cloud, which can be thought of as a vast umbrella that remains neutrally buoyant for extended periods of time but may on occasion undergo a turbulent RT instability leading to the formation of *mammatus pouches* [*Agee*, 1975].) On the other hand, the occurrence of a scalloped umbrella requires that the outer rim of the umbrella become negatively buoyant. As we have seen, the increase in relative density, $\Delta\rho/\rho_d$, need only be moderate—but there must be a loss of neutral buoyancy, or the umbrella will not form scallops.

[17] The rarity of scalloped umbrellas indicates that some unusual conditions must have prevailed in the Reventador column of Figure 2, leading to a ready loss of neutral buoyancy. We propose that the Reventador column was unusually dense and cool. The eruption of 9:12 a.m. appears to have been a steam-rich eruption that entrained cool lithic material from the destruction of a summit cone [*Hall et al.*, 2004]. The erupted material was denser than the atmosphere and formed pyroclastic flows that ran down the slopes of the volcano at the same time as a Plinian column rose over the main vent. Some of the ash was elutriated into the co-ignimbrite column that displayed the scalloped umbrella. We put forward the hypothesis that scalloped umbrellas may be more common on co-ignimbrite columns or mixed co-ignimbrite-Plinian columns than on Plinian columns without surrounding pyroclastic flows, because they contain relatively cool ejecta compared to normal nuées ardentes. Explosive phreatic or vulcanian eruptions might also meet the criteria required for a cool, dense umbrella—and therefore for a scalloped umbrella. Nevertheless, these types of eruption often last for only a fraction of a second to a second. Thus we speculate that the absence of any reports of scalloped umbrellas on columns from phreatic or vulcanian eruptions may be due to the duration of such eruptions, which is short compared with the characteristic time of a turbulent RT instability.

[18] The fate of the scalloped umbrella subsequent to the photographs of Figure 2 was not documented (but may eventually be revealed by field studies of the ash deposits). Most Plinian or co-ignimbrite clouds are buoyant and produce ash falls. Our analysis suggests, however, that the Reventador umbrella could have collapsed back to the ground, forming yet more pyroclastic flows as has been suggested by numerical simulations [*Valentine and Wohletz*, 1989]. These pyroclastic flows would originate at a fallback point quite far removed (kilometers?) from the center of the eruption and could have possessed considerable initial momentum. Furthermore, they could be obscured as the eruption progresses. These likely scenarios should be considered as mapping of deposits is conducted, and in hazards planning.

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