# MAXIMUM AND MINIMUM VOLUME ESTIMATES OF AN ASH FALL LAYER FROM THE AUGUST 2001 ERUPTION OF MT TUNGURAHUA (ECUADOR)

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## INTRODUCTION

After eight decades of quiescence, Tungurahua volcano (5023 m a.s.l.) in the Cordillera Real of Ecuador (Hall et al., 1999) progressively reawakened between August and October 1999. The magmatic activity, which began after a phreatic vent-clearing phase, has been characterized by alternating episodes of gas and ash emissions, short-lived "vulcanian" explosions and strombolian eruptive styles. The intensity of the eruption fluctuated during the year 2000 and decreased drastically in October of the same year. A new eruptive phase started in May 2001 with small-scale lava fountaining, accompanied by occasional "vulcanian" explosions in June and July, and by deep LP seismic events. With no clear immediate precursory warning, a strong increase in tremor amplitude took place on August 04, 2001, marking the onset of a relatively intense strombolian phase which lasted until August 23. The eruptive event coincided with significant rainfall in the area. Wet ash falls and associated acidic rains severely affected livestock and agricultural resources to the west of the volcano, prompting the intervention of several national and international humanitarian organizations.

For various reasons, quantitative tephra volume estimates (ballistics or ash falls) were not obtained during the 1999-2000 eruptive phases. On the contrary, during the relatively intense phase of August 2001 more favorable conditions permitted obtaining reliable thickness measurements within several weeks of the emplacement of the ash fall deposit, which resulted in an isopach map. In this note we present two preliminary estimates of the bulk volume of the ash fall layer. In contrast to most recent studies on tephra fall volume calculations (e.g. Legros, 2000; Pyle, 1995; 1989; Fierstein and Nathenson, 1992), we concentrate here on two simple methods that do not require any mathematical assumption of the thickness decay rate. Estimating the volume of ballistic tephra falls or other eruptive parameters like DRE volumes, magnitude or intensity is beyond the scope of this abstract and will be presented in forthcoming notes.

## DATA COLLECTION

Ninety thickness measurements were made during and after the eruptive phase. Twelve isopachs in the thickness range 0.3 – 12 cm were contoured on a map with satisfactory precision. We also attempted to assess the area of two additional isopachs based upon the following arguments. On the Pan-American highway a thickness of 0.2 cm of ash was measured 28 km downwind from the volcano. Considering an elliptical isopach 28 km long and 14 km wide we obtain an area of 308 km$^2$. In addition, the icecap of Chimborazo volcano, located about 50 km west of Tungurahua, appeared coated with a dark layer of ash at the end of the eruption. By analogy with what we have observed at many other localities, we think that a minimum thickness of 0.05 cm is required to obtain such a uniform ash cover. This permitted us to relate the area of the 0.05 cm isopach to that of an ellipse 50 km-long and 20 km-wide. Data of isopach thicknesses and areas are given in Le Pennec et al. (2002), along with results of others estimates of bulk ash fall volume.

## ASH FALL THICKNESS VARIATIONS AND VOLUME ESTIMATES

Pyle (1989) and Fierstein and Nathenson (1992) have shown that the data (thickness, $T$ – isopach area, $A$) of many natural deposits plot as one or two straight lines on a Log$T$ – $A^{1/2}$ diagram. From these and other findings, Houghton et al. (1999) concluded that the thickness of proximal and medial tephra fallout deposits decay exponentially with distance from the source. For this reason, most models of tephra fall volume calculations are based on the exponential decay assumption (e.g. Legros, 2001; Pyle, 1995; 1989; Fierstein and Nathenson, 1992).

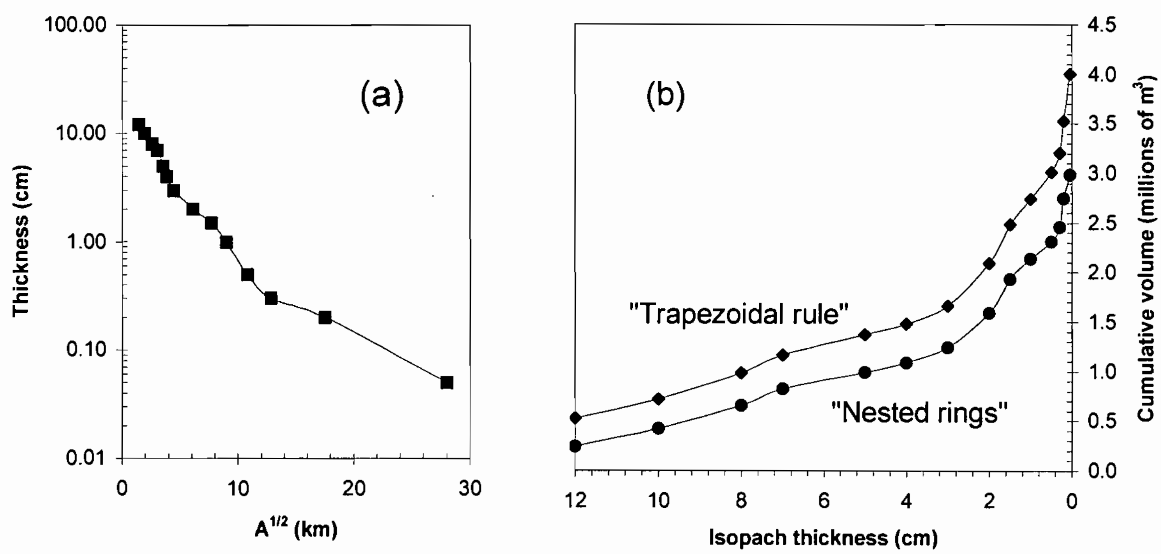


**Figure 1. (a)** Plot of Log$T$ versus square root of isopach area. **(b)** Cumulative volume against isopach thickness from 12 cm to 0.05 cm using the "trapezoidal rule" (upper curve) and the "nested rings" (lower curve) approximations.

However, other studies point out limits to this widely accepted model. For example, Bonadonna et al. (1998) modeled the influence of particle Reynolds numbers on final tephra fall thickness. They found that coarse ejecta with high Reynolds numbers should correspond to a deposit displaying an exponential decay rate. On the other hand, settling of fine-grained ash with low Reynolds numbers should form a deposit whose thinning rate is better described by a power law.

Various other processes may lead to additional departures from the exponential decay rate model. For instance, the effect of ash aggregation or the control of rain flushing on the final thinning rates is poorly known. These processes were at work during the August 2001 eruptive phase of Tungurahua volcano. Moreover, work in progress suggests that the deposit contained a significant fraction of low Reynolds number particles, even close to the source. Altogether, this may partly explain the complex thinning rate observed at Tungurahua (Figure 1a). Because the thinning rate does not clearly follow the simple exponential decay rate model, we propose here to simply evaluate the bulk volume of ash using two extreme models which do not require any assumption on the mathematical formulation of the decay rate. Below we use first a method called the "trapezoidal rule" approximation that has been applied to pyroclastic deposits by various authors (e.g. Fierstein and Nathenson, 1992 and references therein) to calculate a maximum bulk ash fall volume. Secondly, a new method is presented here, called the "nested rings" approximation. It allows estimating a minimum bulk volume of the deposit.

**"Trapezoidal rule" approximation.** This method overestimates the true volume (see details in Fierstein and Nathenson, 1992). However, it tends to give reasonable maximum values, if closely spaced isopachs are provided and if a $T = 0$ isopach can be defined. In this method the thinning rate is a discontinuous function of the isopach area and the thickness varies linearly with area between two successive isopach data. Here we need an estimate of $T_0$, the ash fall thickness at the vent. According to a mountain climber who reached the crater in December 2001, the fallout thickness on the northern crater rim was about 40-60 cm (Alexander García, pers. comm., 2001). Because the dispersal axis was oriented to the west of the crater, and because the crater rim is still situated about 100 m from the major eruptive vents, we have assigned a value of 80 cm for $T_0$. The second problem is to estimate the area of the isopach $T = 0$. If we consider the dispersion of the ash monitored by NOAA satellites, along with witness accounts of ash fall near the Ecuadorian coast, we propose that the westernmost limit of the $T = 0$ isopach coincided with the 81° meridian, offshore of the Ecuadorian coast. We thus approximate the $T = 0$ isopach area to that of a 300 x 80 km ellipse. Finally, we obtain a bulk cumulative volume $V_{tr}$ (subscript "tr" is for "trapezoidal rule") of 3.61 x $10^6$ $m^3$ if the most distal isopach has a thickness $T_d = 0.3$ cm (Figure 1b); 4.41 x $10^6$ $m^3$ if $T_d = 0.05$ cm, and 8.93 x $10^6$ $m^3$ if $T_d = 0$. This latter value should represent a maximum estimate of the ash fall layer volume.

**"Nested rings" approximation.** This method is newly defined here and consists in dividing the ash fall layer in a succession of concentric structures (or eccentric structures if isopach contours are elliptical in shape), each being bounded by two isopachs of thickness $T_n$ and $T_{n+1}$ (with $T_n > T_{n+1}$), corresponding to areas $A_n$ and $A_{n+1}$ ($A_{n+1} > A_n$) respectively. Between $T_n$ and $T_{n+1}$ the thickness is supposed to be constant and equal to $T_{n+1}$. This method does not necessitate extrapolating the thinning rate neither to the vent nor to infinity but requires many closely spaced isopachs to provide an acceptable minimum volume. Application to our data collection gives a cumulative volume $V_{nr}$ (subscript "nr" is for "nested rings") of 2.46 x $10^6$ $m^3$ if the most distal isopach has a thickness $T_d = 0.3$ cm; 2.75 x $10^6$ $m^3$ if $T_d = 0.2$ cm, and 2.98 x $10^6$ $m^3$ if $T_d = 0.05$ cm. This latter value should represent a minimum estimate of the ash fall layer volume (Figure 1b).

## CONCLUSION

Sustained strombolian activity took place at Tungurahua volcano in the Ecuadorian Andes in August 2001. The three weeks long eruptive phase produced a notable plume of ash whose deposits were concentrated by strong to moderate winds to the west of the edifice. With two complementary methods we have estimated a maximum and a minimum volume for the ash fall deposit. Using thickness extrapolations to the vent and distally to zero, the "trapezoidal rule" approximation gives a maximum volume $V_{tr}$ close to 9 x $10^6$ $m^3$, while the "nested rings" approximation provides a minimum volume $V_{nr}$ close to 3 x $10^6$ $m^3$, i.e. only three times smaller than the maximum volume $V_{tr}$. The average of these two extreme volumes is 6 x $10^6$ $m^3$, in close agreement with other preliminary volume estimates based on exponential or power law thinning rate assumptions (Le Pennec et al., 2002). The August 2001 ash fall layer is thus remarkably small if compared to other tephra falls deposited during the recent (<3000 yr BP) geological history of the volcano (Hall et al., 1999). In summary, the August 2001 eruptive phase of Tungurahua volcano illustrates how a small-size eruption can have a pronounced impact on human activities and properties, twenty-three months after the onset of the magmatic activity.

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