Appendix DR1. Methods

Samples were sieved to integer phi size intervals. Ash particle mounts created for at least two single phi size intervals for each sample (between phi sizes 1 and 4) were scanned in Backscattered Electron (BSE) mode (10keV, 10-20nA beam) using a JEOL 6300 Scanning Electron Microscope at the University of Oregon. Images were taken at several different scales to resolve textural variations in crystal content among particles. Ash particle counts were made on 50 – 150x images (with the exception of the finest particles, which were imaged at 500x) for a minimum of 50 to 500 ash particles, the number depending on sample heterogeneity. For electron microprobe analyses, we used a 5μm diameter defocused beam and a volatile correction to account for sodium loss in glass, and a focused beam for feldspar crystals.

### TABLE DR1.

<table>
<thead>
<tr>
<th>Sample locality</th>
<th>Sample date</th>
<th>Number of ash grains counted in each class</th>
<th>Percentage of counted grains of each class</th>
<th>Average crystallinity</th>
<th>St error crystallinity</th>
<th>St dev crystallinity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>sum</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Hcda Guadalupe</td>
<td>13-Nov-99</td>
<td>62</td>
<td>9</td>
<td>7</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>Chacacou</td>
<td>14-May-00</td>
<td>48</td>
<td>39</td>
<td>20</td>
<td>38</td>
<td>72</td>
</tr>
<tr>
<td>Hcda Guadalupe</td>
<td>25-Sep-00</td>
<td>48</td>
<td>73</td>
<td>67</td>
<td>152</td>
<td>61</td>
</tr>
<tr>
<td>Pillate</td>
<td>15-Apr-01</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>summit</td>
<td>02-Nov-01</td>
<td>106</td>
<td>86</td>
<td>65</td>
<td>58</td>
<td>76</td>
</tr>
<tr>
<td>S of Quero</td>
<td>05-Apr-02</td>
<td>35</td>
<td>86</td>
<td>44</td>
<td>83</td>
<td>70</td>
</tr>
<tr>
<td>Pillate</td>
<td>04-Aug-02</td>
<td>12</td>
<td>6</td>
<td>13</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Cusua</td>
<td>18-Jun-03</td>
<td>151</td>
<td>110</td>
<td>58</td>
<td>51</td>
<td>44</td>
</tr>
<tr>
<td>Cusua</td>
<td>06-Sep-03</td>
<td>139</td>
<td>56</td>
<td>41</td>
<td>28</td>
<td>36</td>
</tr>
<tr>
<td>Banos</td>
<td>01-Nov-03</td>
<td>44</td>
<td>21</td>
<td>9</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Pillate</td>
<td>17-Jul-04</td>
<td>43</td>
<td>22</td>
<td>14</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>18-Aug-06</td>
<td>85</td>
<td>12</td>
<td>6</td>
<td>5</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>

Crystallinity = %class1*.29+%class2*.38+%class3*.45+%class4*.57+%class5*.67+%class6*.04

where %class# = percentage of counted grains of each class.
Direct and indirect estimates of emitted material at Tungurahua volcano between 1999 and 2004


1. Introduction

The eruption sequence at Tungurahua volcano beginning in 1999 consisted of a succession of Strombolian – Vulcanian phases of varied intensity. High intensity episodes were characterized by continuous, and sometimes forceful ash emission, explosions of moderate size (column height to 4-5 km above crater level) and lava fountaining episodes. Phases of low activity included vapor and gas emission, including one low activity phase that continued for seven months.

Erupted ash settled over a vast area in Central Ecuador, principally to the west of Tungurahua volcano (Fig. 1). On many occasions, ash falls severely impacted communities living near the volcano, in some cases causing serious problems for the agricultural and tourist industries, the physical health of local residents, and the regional economy. Given these problems, the Ecuadorian government declared a state of emergency for the impacted provinces in August 2001 and August 2003 (ratified in 2004). The volcanological community was solicited to appraise the size of each eruptive phase. For sulfur-dioxide gas emissions, this was accomplished using remote Correlation Spectrometer (COSPEC) measurements. However, estimating the amount of solid material erupted by the volcano is a more difficult task because the plume is widely dispersed and ash fall layers are very thin and rapidly eroded by wind and rain. This problem is especially true for small eruptive events. Only one eruptive phase over this period was strong enough to emplace a tephra fall layer of measureable volume (August 2001). A detailed study of volume estimation is presented in Le Pennec et al. (2002, 2004).
In this note, we present the first estimate of tephra fall volume using volcanic plume equations that model the height of volcanic ash column based on the emission rate estimated for the Tungurahua case. The estimates rely on the observed plume elevations (database continuously fed by the Geophysical Institute-National Geophysical School, IG and the Volcanic Ash Advisory Committee, VAAC), emission volumes (specifically calculated for August 2001, cf. Le Pennece et al. 2002, 2004) and calculations of atmospheric stratification, as provided by the Ecuadorian Meteorological Agency (INAMHI, 2004).

2. Ash Dispersal Patterns

The ash clouds were dispersed across central mainland Ecuador, in some cases reaching the Pacific Ocean to the west and Colombia and Peru to the east. Ash advisory reports produced by IG and VAAC were highly valuable to air traffic control. This information included the time of the explosion, approximate height and width of the plume, and the relative ash content of the plume (high, moderate, low).

During the first eruptive phase in 1999, the ash plumes were largely dispersed across the entire country (Fig. 2). Activity waned in 2000 and the plumes were mostly reported across the central part of Ecuador (Fig 3).
**Figure 2.** Dispersal pattern of ash cloud during 1999 eruption episodes (September, December).
Eruptive activity remained at low levels during the first half of 2001, but new lava fountaining episodes were followed by the reappearance of discrete cannon-like explosions in June. The increased intensity peaked in August 2001 with an intense, three-week-long Strombolian phase that deposited a notable ash fall to the west of the volcano. Light ash fall was reported in the Guayaquil region and elsewhere on the Ecuadorian coast. The fine ash fraction was distributed over a vast area and the plume was visible 1000 km from the volcano. (Fig. 4)
During 2002, the activity returned to a lower intensity than that of the late 1999 or August 2001 periods, although explosions and emissions were frequent, as during the January-September 2000 period. This is apparent in the limited distribution of ash over this time period (Fig. 5).
The intensity of the activity increased again around mid-2003 and lasted until December 2003. Over this interval, dispersal was widespread across the country (Fig 6). Ash emissions severely impacted local agricultural resources and caused air traffic to be diverted around the plume.
The volcano remained active in 2004, but activity generally decreased in intensity. This lower intensity is visible in Fig. 7 where the distribution is similar to that reported for 2000 and 2002.
Climactic conditions played an important role in the actual distribution of the plumes and their associated deposits. During the strong August 2001 phase the low-level rain precipitated the deposition of ash, thus facilitating thickness measurements at many localities.

The visual observation of the ash clouds from the observatory and through satellite tracking (VAAC) has allowed us to plot the frequency of ash clouds with wind direction. The plot shows the predominance of westerly winds but all other directions are also represented, i.e. to a lesser extent to the SW, NW, E and N. These data are useful as reference pattern for the preferred direction of the ash plumes.
Figure 8. Frequency plot for wind directions in the Tungurahua region between 1999 and 2004.

The maximum reported elevation for the ash cloud over this time interval was 18 km above sea level in November 1999 and the minimum elevation is the elevation of the crater. The height of the ash column is broadly correlated with the energy released by surface seismic waves (Fig. 9).
The plumes drifted in all directions and the highest wind speeds were recorded when the plume moved toward the SE, WSW and NW (Fig. 10), consistent with the dominating wind speed occurs toward the West. These data are required to derive SO2 output measured with COSPEC instruments (Fig 11).

Figure 10. azimuth and velocity of ash clouds from Tungurahua volcano
4. Models of Volcanic Plume Dynamics

Volcanic plumes are mixtures of hot gas and ash that are ejected at high velocity, and form a convecting cloud before drifting by winds and dispersing into the atmosphere. The distribution and fall of this material is chiefly controlled by the elevation attained by the material, the velocity of the particles and the direction, and speed of the wind. In simple terms, these parameters determine the path of any clast in the volcanic plume during transport and deposition (Carey and Bursik 2000; Sparks et al. 1997).

Volcanic plumes are generated when magma is fragmented into small pieces (pyroclasts) and discharged from the volcano at high velocity. Volcanic plumes can be dispersed on a global scale (e.g., Pinatubo 1993). Many different eruption styles produce volcanic plumes, and their behavior is controlled by factors such as: magma composition, nature and volume of volatile gases, and vent geometry (Carey and Bursik 2000). In the largest eruptions, a plume can reach altitudes of up to 50 km. Some plumes can be maintained for relatively long time periods, due to continuous discharge of material from the vent. For example, the May 18, 1980 eruption of Mount St. Helens produced a volcanic plume for over 9 hours (Carey and Bursik 1980). In other cases, discrete ejections of gas and particles can last a few minutes. Small and low energy eruptions produce volcanic plumes that spread laterally in the troposphere (<18 km).

Magmatic fragmentation is caused by exsolution of volatile species (H₂O, CO₂, SO₂) in the volcanic reservoir. Fragmentation can also occur due to intersection of magma with a groundwater aquifer, which explosively superheats the water.
The Tungurahua eruption remained relatively small in size until the 2006 summer eruptions. The size of the Tungurahua eruption is difficult to assess, but there is a need for accurate estimation of size for surveillance purpose etc. For example, the August 2001 episode had a VEI index of 2 if the fall layer is considered. On the other, when the ballistic component is considered, the VEI might have reached 3. The eruption style was essentially sustained Strombolian style, therefore the plume dynamics can be approximated to a purely thermal plume. In this context we perform here the adjustment and calibration of the equations that control the maximum column elevation (Sparks et al. 1997).

\[ H_T = K F_T^{1/4} N^{-1/2} \]

Where:
- \( H_T \): Maximum elevation of the ash cloud (m)
- \( F_T \): Product of the buoyancy and volume of the plume (m\(^4\) s\(^{-2}\))
- \( N \): Atmospheric stratification (s\(^{-1}\))
- \( K \): Nondimensional calibration constant (for Tungurahua)

\( F_T \) is given by

\[ F_T = V_{T_0} g(T_{T_0} - T_a) / T_a \]

- \( V_{T_0} \): Initial volume of the plume (m\(^3\))
- \( T_{T_0} \): Initial temperature (K)
- \( g \): Gravitational constant (m s\(^{-2}\))
- \( T_a \): Atmospheric temperature at elevation \( H_T \) (K)

### 5. Calibration of Volcanic Plume Equations for Tungurahua

The IG has monitored Tungurahua volcano since 1993, recording an increase in seismic and fumarolic activity beginning in 1999, culminating in the magmatic eruption later that year.

To calibrate the Sparks et al. equations we use the explosion and emission record for Tungurahua and the atmospheric results obtained by INAMHI.

The August 2001 eruption produced favorable conditions for estimation of the volume of tephra fall deposits. Although different result are obtained according to which method is used to estimate the tephra fall volume (i.e. trapezoidal rule approximation vs. exponential decay vs. power law decay) we considered that about 6*10\(^6\) m\(^3\) of unconsolidated ash accumulated mainly to the west of the edifice.

During this sustained eruptive period, 133 explosions and 1488 emissions were recorded by the seismic network installed by the Geophysical Institute (IG; Fig. 12).

At the same time, the GOES-EAST (NOAA) identified 72 images of volcanic clouds and catalogued their respective elevations. These data allow us to estimate the average discharge rate of each event as well as the mean altitude of the August 2001 ash clouds.
(3) erupted volume (per event) = deposited volume / (number of explosions + number of emissions)

Which yields an erupted volume of 3,700 m$^3$ per event during August 2001.

The discharge rate is obtained by dividing the deposit volume by the duration of the event (set as 20 days, from August 4 to 24). The mean volumetric discharge rate therefore was 3.5 m$^3$ s$^{-1}$ over this time interval.

Similarly the mean elevation, $H_T$, of the ash cloud can be obtained by dividing the sum of the measured plume elevations by the number of events registered by the GOES-EAST satellite, yielding $H_T = 8.2$ km above sea level. This is in agreement with ground-based observations from the observatory, which indicated that the plume was about 3 km above crater level, and consistent with the measured altitude during all intense eruptive periods.

We assume thermal equilibrium between the molten magma and the escaping gases and set a mean eruption temperature of 900°C at the vent. The atmospheric temperature, $T_a$, at different elevations is determined as a function of elevation, according to an established temperature gradient (Sparks et al., 1997). This is applied to the maximum height for the ash columns, as given in the IG-EPN database.

$T_a = 2$

$T_{T0} = 900 \degree C = 1173$ K

Stratification parameter $N = 4.9$ s$^{-1}$

The constant, $K$, in equation 1, is obtained by substituting equation 2 into equation 1, using the aforementioned values of $H_T$, $T_a$, and $T_{T0}$ for August 2001. The resultant $K$ is found to be 912 and is applied to all ash cloud elevations from the IG-EPN VAAC database.
Applying Equations 1 and 2

We apply this calibration to the database of the ash cloud heights, obtained from the VAAC reports of the GOES-EAST.

\[ H_T = 912 \frac{F_T}{N^{1/2}} \]

From equation (1) we obtain \( F_T \), which is the product of the thermal plume volume with the initial buoyancy. We then use this value of \( F_T \) in equation (2) to calculate the volume erupted during each event. However, the VAAC database underestimates true plume heights; it is therefore necessary to adjust the cumulative volume curve (IG-VAAC) to the August 2001 results, so as to obtain a correction factor defined by \( FC = \) deposited volume of August 2001 / calculated volume (from IG-VAAC) for August 2001.

The calculated FC value is 17.64

This correction factor is applicable to all periods similar to the August 2001 phase. For low intensity periods we consider a direct relationship with the slope of the cumulative volume curve (Fig. 13). We assign different correction factors for different average slopes, as follows:

- Slope August 2001 (8.144) \( FC = 17.64 \)
- Slope 0.933 \( X = 2.02 \) (FC2)
- Slope 0.700 \( X = 1.52 \) (FC3)

For slopes lower than 0.7 (units??) we made no adjustment of the curve because the intensity is assumed to be very low, and the ash clouds recorded by VAAC are consistent with the level of eruptive activity.

From these calculations, we therefore arrive at a total emission volume between October 1999 and December 2004 of \(~2.6 \times 10^7\) m³ of unconsolidated material, distributed chiefly in Central Ecuador (Fig 13).

![Figure 13 Cumulative tephra volume erupted from Tungurahua from October 1999 to December 2004.](image)
Conclusion

Volcanic ash clouds from Tungurahua spread over most of Ecuador, dominantly in a westward direction. The dispersal is correlated to the wind direction and speed as well as with the level of activity at the volcano. The existence of the Intertropical Convergence Zone permits circulation of winds from North to South giving rise to the formation of an atmospheric cloud belt that tends to move toward the south through the year. This system partly controls the displacement of the volcanic clouds in central Ecuador. However, there are many departures from this ‘average’ behavior, including consistent seasonal variations. Atmospheric perturbations in the Amazon permit the formation of vertically extensive and convective clouds. In this zone, winds circulate from the east to the west, causing clouds to migrate towards the Andes mountain belt. In this way, the area of Ecuador near Tungurahua forms a window, where cloud mass enters towards the InterAndean Valley. Under these conditions, ash clouds were dispersed in different directions, sometimes causing diversion of air traffic towards more secure routes. These ash clouds were restricted to the troposphere, and in this manner, their dispersal was not global, but local.

Ash fall created serious problems for the agricultural and commerce industries in the area. Because most ash falls were relatively small and the deposits were commonly ephemeral, we realized the need to estimate erupted volumes. Fortunately, there were some events (particularly those in August 2001) that were large enough to measure ash deposit thickness; these events were used to calibrate volcanic plume dispersal equations. Using these calibrated equations, the height of the erupted plume can be used to directly determine approximate erupted volume.

The total volume calculated for the 1999-2004 period is $2.6 \times 10^7$ m$^3$ of unconsolidated ash, and includes contributions from periods of higher and lower activity. There is uncertainty in this model, due to the relatively simple nature of the volume determinations, which do not include complex models of gas and particle diffusion in the atmosphere. The calibrated equation from this work will help inform future work on volcanic ash in Ecuador.

References


Departamento de Geofísica, Escuela Politécnica Nacional, Base de datos Tungtotal2004 backup.


INAMHI (Instituto Nacional de Meteorología e Hidrología) – Base de datos departamento de Sinóptica –2004.


