

Influence of the wind direction variability on the quantification of tephra fallouts: December 2012 and March 2013 Tungurahua eruptions

Benjamin Bernard^{1*}, Jorge Bustillos², Bridget Wade^{1,3} y Silvana Hidalgo²

¹Universidad San Francisco de Quito, Colegio Ciencias e Ingeniería - el Politécnico. Diego de Robles y Vía Interoceánica, Campus Cumbayá, Casa Tomate. Casilla Postal 17-1200, Quito, Ecuador.

²Instituto Geofísico, Escuela Politécnica Nacional de Quito. Calle Ladrón de Guevara E11-253. Casilla Postal 17-2759, Quito, Ecuador.

³Juniata College. 1700 Moore Street. Casilla Postal 16652, Huntingdon, United States of America.

*Autor principal/Corresponding author, e-mail: bbernard@usfq.edu.ec

Editado por/Edited by: Cesar Zambrano, Ph.D.

Recibido/Received: 02/05/2013. Aceptado/Accepted: 30/05/2013.

Publicado en línea/Published on Web: 28/06/2013. Impreso/Printed: 06/06/2013.

Abstract

The quantification of tephra fallouts can be affected by different parameters such as the quality of the deposit exposure and the calculation method. In this paper the effect of variability in the wind direction is investigated through the analysis of two eruptions from the Tungurahua volcano in Ecuador. The fluctuation in the wind direction was assessed using the alerts generated by the Washington VAAC (Volcanic Ash Advisory Center) and the actual fallout reports from local volunteers. Area densities (mass/area) of the tephra deposits were compiled by each co-author to create isomass maps. Empirical methods were used to calculate the total mass of the tephra fallouts. With this approach we were able to study the influence of the wind direction variability on the quantification of tephra fallouts under similar eruptive and sampling conditions. Our results indicate that, due to higher wind direction variability, the December 2012 eruption produced a non-elliptical complex deposit with a larger uncertainty on the calculated total mass value. The March 2013 eruption, on the other hand, occurred during a period of steady wind direction and left an almost elliptical deposit. The compilation of the data from the March eruption done by the co-authors demonstrates greater coherence and a less uncertainty in the final result. This study highlights that the choice of the empirical law to describe the fallout distribution must be adapted according to the map of the deposit.

Keywords. Fallout quantification, wind direction, Tungurahua, isomass maps, tephra, physical volcanology.

Resumen

La cuantificación de caídas de tefra puede ser afectada por diferentes parámetros, tales como la calidad de exposición de los depósitos y los métodos de cálculo. En este trabajo se investiga el efecto de la variabilidad de la dirección del viento a través del análisis de dos erupciones del volcán Tungurahua (Ecuador). La fluctuación de la dirección del viento se analizó usando los reportes de la Washington VAAC (Volcanic Ash Advisory Center) y los reportes de caída de ceniza real proporcionados por los vigías del volcán. Los datos de densidad areal (masa/área) de los depósitos de tefra fueron compilados por cada uno de los co-autores para la realización de los mapas de isomasas. Se utilizó métodos empíricos para calcular la masa total de la caída de tefra. Por primera vez ha sido posible estudiar la influencia de la variabilidad de la dirección del viento en la cuantificación de la caída de ceniza bajo similares condiciones eruptivas y de recolección de muestras. Los resultados de este trabajo muestran que, debido a una mayor variabilidad de la dirección del viento, la erupción de diciembre de 2012 produjo un depósito complejo cuyas isomasas tienen formas no elípticas con una mayor incertidumbre en el valor de la masa total. Por el contrario, la erupción de marzo 2013 se produjo durante un período en el que la dirección del viento fue constante y dejó un depósito de forma casi elíptica. La recopilación de los datos de marzo realizadas por los co-autores muestra una mayor coherencia y por lo tanto una menor incertidumbre en el resultado final. Finalmente, este trabajo destaca el hecho de que la elección de la ley empírica para describir la distribución del depósito debe tomar en cuenta el mapa del mismo.

Palabras Clave. Cuantificación de caída, dirección del viento, Tungurahua, mapas de isomasas, tefra, vulcanología física.

Introduction

The total volume and mass of tephra fallouts are essential volcanological data since they provide significant insight into the magnitude and explosivity of a volcanic eruption [1]. This information is also used in numerical modeling to facilitate the forecasting of volcanic plume dispersal and tephra fallouts [2]. The most widely used methodology to calculate total volume and mass of fallouts is based on a three step procedure: 1) measurements of thickness and area density (mass/area) of the tephra deposit in different locations; 2) interpretation and compilation of the data into isopach and isomass maps; 3) calculation using empirical laws that describe the distribution of the deposit around the vent [3–5]. This procedure can be affected by a large number of parameters such as the quality of the field data, the uncertainty in the isopach and isomass map compilation, and the empirical law used (e.g. exponential versus power-law). Several studies with a primary focus on the availability of data and the accuracy of the empirical laws have been carried out to assess the uncertainty of fallout volume calculation [6, 7]. Nevertheless some aspects of this quantification process are still sidelined from the scientific debate.

Volcanic plumes responsible for tephra fallout are affected by the wind and will ideally produce an elliptical deposit with the main axis of the ellipse corresponding to the main wind direction and one focus of the ellipse encompassing the volcanic vent [3]. This characteristic was used to define the first commonly accepted empirical law based on the apparent exponential thinning of the deposit away from the vent [3]. The direction of the wind may shift over the course of an eruption, especially for long lasting eruptions, affecting the distribution of the tephra deposit around the volcano and therefore changing the shape of the isopachs and isomasses. If this aspect has already been assessed to produce more reliable empirical laws [4], it has never been investigated for its effects on the interpretation of the data and drawing of the deposit maps. Therefore, this paper proposes to study the influence of the wind direction variability on the calculation of the total mass and volume of tephra.

To assess the effects of the wind on this quantification, it is important to compare eruptions with similar size and sampling networks. The Tungurahua volcano (Ecuador) has been in eruption for almost 14 years, repeatedly producing tephra fallout that affect thousands of square kilometers [8, 9]. Since 2007, Tungurahua tephra deposits have been systematically sampled due to the establishment of a network of ash collectors [10, 11]. This network has recently been expanded to include a more distal area and modernized with the use of homemade ashmeters that permit more accurate and systematic measurements [12]. Tungurahua's eruption is not continuous and since 2008 the volcano has presented short to medium-lived eruptions, spanning from a few days to

a few weeks, and separated by periods of quiescence ranging from two to six months. These periods of inactivity permit detailed studies of each precedent eruptive period and associated tephra deposits. In the Eastern Cordillera of Ecuador, where the Tungurahua volcano is located, the wind mainly blows from the Amazonian basin to the Pacific Ocean (east to west) most of the year. However, it is common to have much variable wind directions between November and January. Eruptions occurring at different periods of the year produce volcanic plumes carried in different directions due to changing atmospheric currents.

Methodology and sampling

For this study we analyzed the last two eruptions from Tungurahua, in December 2012 and March 2013. Both eruptions lasted for approximately the same amount of time, 17 and 18 days respectively, with millimeter-thick deposits in the proximal area. It is extremely difficult to obtain precise meteorological data in Ecuador due to the scarcity of meteorological stations as well as the complexity of the atmospheric stratification resulting from geography and topography. During an eruption the wind direction can be inferred from observations of the volcanic plume direction and from the pattern of tephra fallout. We used two independent sources of information to study the wind direction variability: 1) the Washington VAAC (Volcanic Ash Advisory Center) which emits alerts whenever a volcanic plume is identified by airplane pilots or on satellite images; 2) the Tungurahua Volcano Observatory of the IG-EPN (Instituto Geofísico de la Escuela Politécnica Nacional) which compiles observations on tephra fallout around the volcano from a network of local volunteers. This information is plotted in rose diagrams in order to determine the principal directions of dispersion of the volcanic plume and tephra fallout.

Two field missions, from the 11th to the 13th of January (December 2012 eruption) and from the 27th to the 28th of March (March 2013 eruption), were carried out to collect the tephra accumulated in the ashmeters. For the March 2013 eruption some samples from the northernmost region of the network were collected during the first week of April. Thickness readings were made directly in the field, and the samples were dried at 40°C and weighed in the Universidad San Francisco de Quito geology laboratory. The data was collected in 42 and 47 locations for the December 2012 and March 2013 eruptions respectively. The most proximal datapoint is 6 km from the vent and the most distal datapoint is 32 km from the vent. Area density (mass/area) was calculated in all sites with a 1 g/m² precision to compile isomass maps and calculate the eruptions' total mass of tephra. Thickness readings were possible only in few places (7 and 12 locations for the December 2012 and March 2013 eruptions respectively) due to the lower limit of the ashmeter scale (0.3 mm). Thickness measurements were used to calculate bulk densities in or-

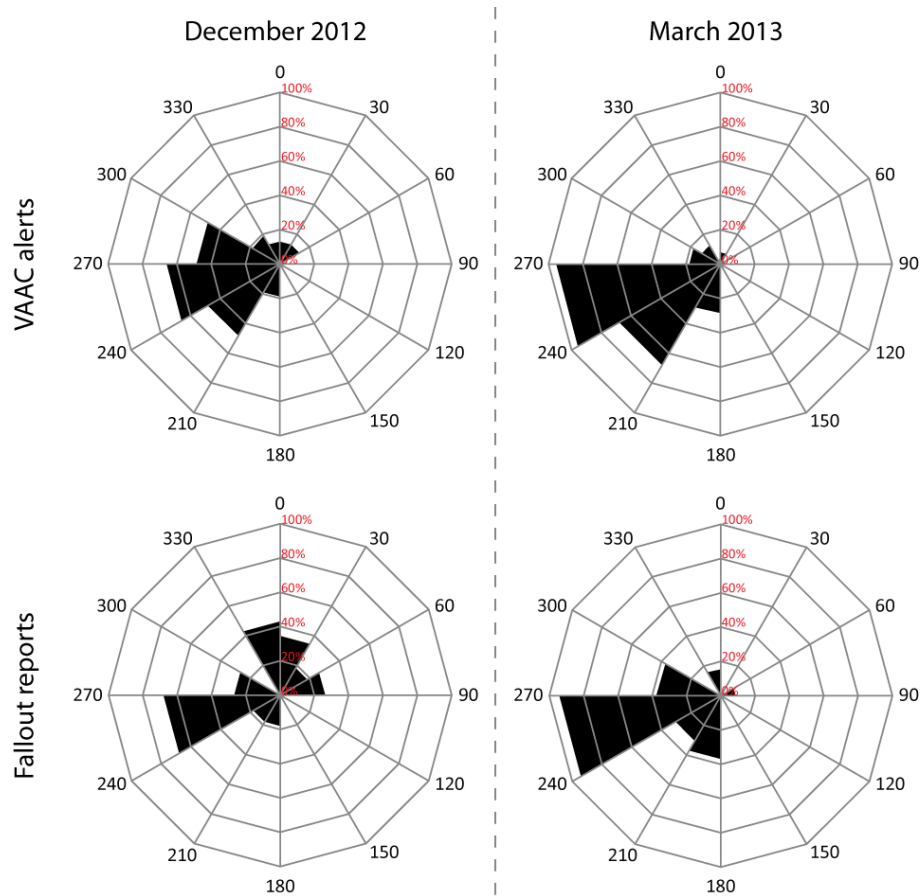


Figure 1: Rose diagrams of the Washington VAAC alerts (source: www.ospo.noaa.gov) and the fallout reports (source: www.igepn.edu.ec) for the December 2012 and March 2013 Tungurahua eruptions

der to ultimately estimate the eruptions' total volume of tephra. The isomass maps were drawn on a geospatial processing program for each eruption by each of the co-authors without exchange of information other than the raw database. Each co-author has a different approach and background in drawing isomass maps.

In the past 25 years, several models using isopach and isomass maps have been proposed to calculate the total volume and mass of tephra fallouts [3–6, 13]. These models involve the best fitting of thinning data using empirical laws (i.e., exponential law with one or more segments, power law, Weibull function) on semilog plots of thickness (or area density) versus square root of isopach (or isomass) area. Ultimately, the choice of the empirical law is based on the availability of data and the pattern of thinning of the tephra deposit.

Results

Volcanic plume directions and fallout reports

During the December 2012 eruption, the plume direction reported by the Washington VAAC and the fallout observations reported by local volunteers indicate that the eruption affected a very wide range of sectors (Figure 1). The plume directions are concentrated to the west of the volcano, from SW to WNW, although more

than 10% of the days have plumes drifting to the north and to the south. The fallout reports exhibit a slightly different distribution with zones heavily affected by ash fall to the WSW and NNW. For more than 20% of the days, significant fallouts were also reported in the WNW, NNE and ENE quadrants. There are some discrepancies between the information obtained from the Washington VAAC and the fallout reports, especially for the northern and eastern sectors. These differences can be associated with the timing of the changes in wind direction and the atmospheric conditions. The wind blew north and north-east with dry atmospheric conditions and heavy tephra fall at the beginning of the eruption. After three days, the wind direction shifted gradually west coinciding with a slight decrease in the rate of fallout. It is therefore probable that parts of the reports from the northern and eastern sectors are attributed to episodes of remobilization of the tephra deposits, affecting the populated area even if the actual volcanic plume drifted westward. Another possible explanation for the discrepancy is that, given the cloud coverage during this period of the year, the Washington VAAC was unable to identify part of the low altitude plumes that drifted north and east.

For the March 2013 eruption, the VAAC alerts and fallout reports both coincide neatly, manifesting a narrower range of sectors affected by the tephra fallout. The WSW

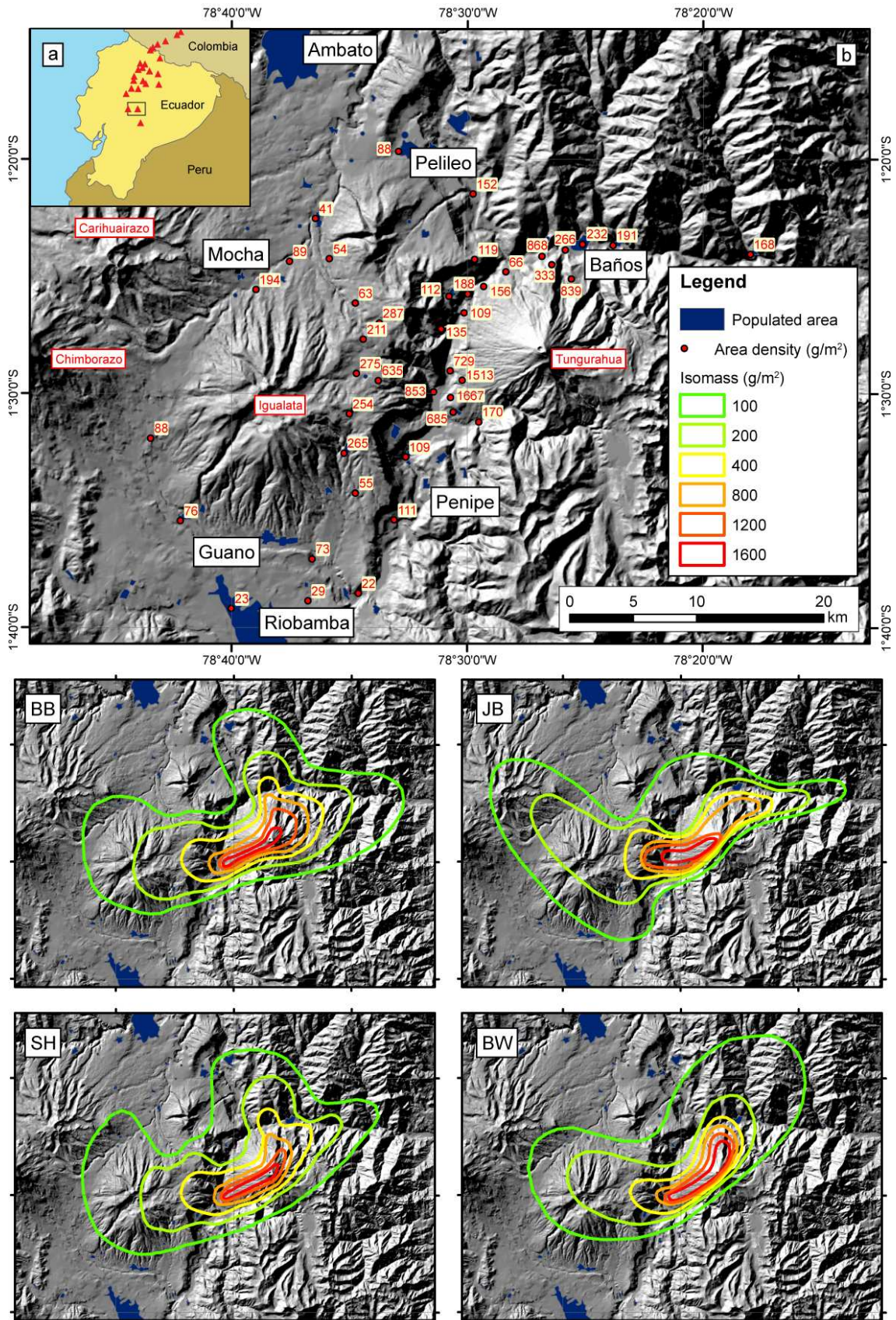


Figure 2: Location map of Tungurahua volcano in the Ecuadorian Volcanic Arc. b. Shaded relief map of the sampling network with the area density value (in g/m²) of the December 2012 Tungurahua eruption. BB, JB, SH, BW: isomass maps named after the initials of the co-authors of this study. In black: names of the main towns of the area. In red: names of the main volcanoes in the area.

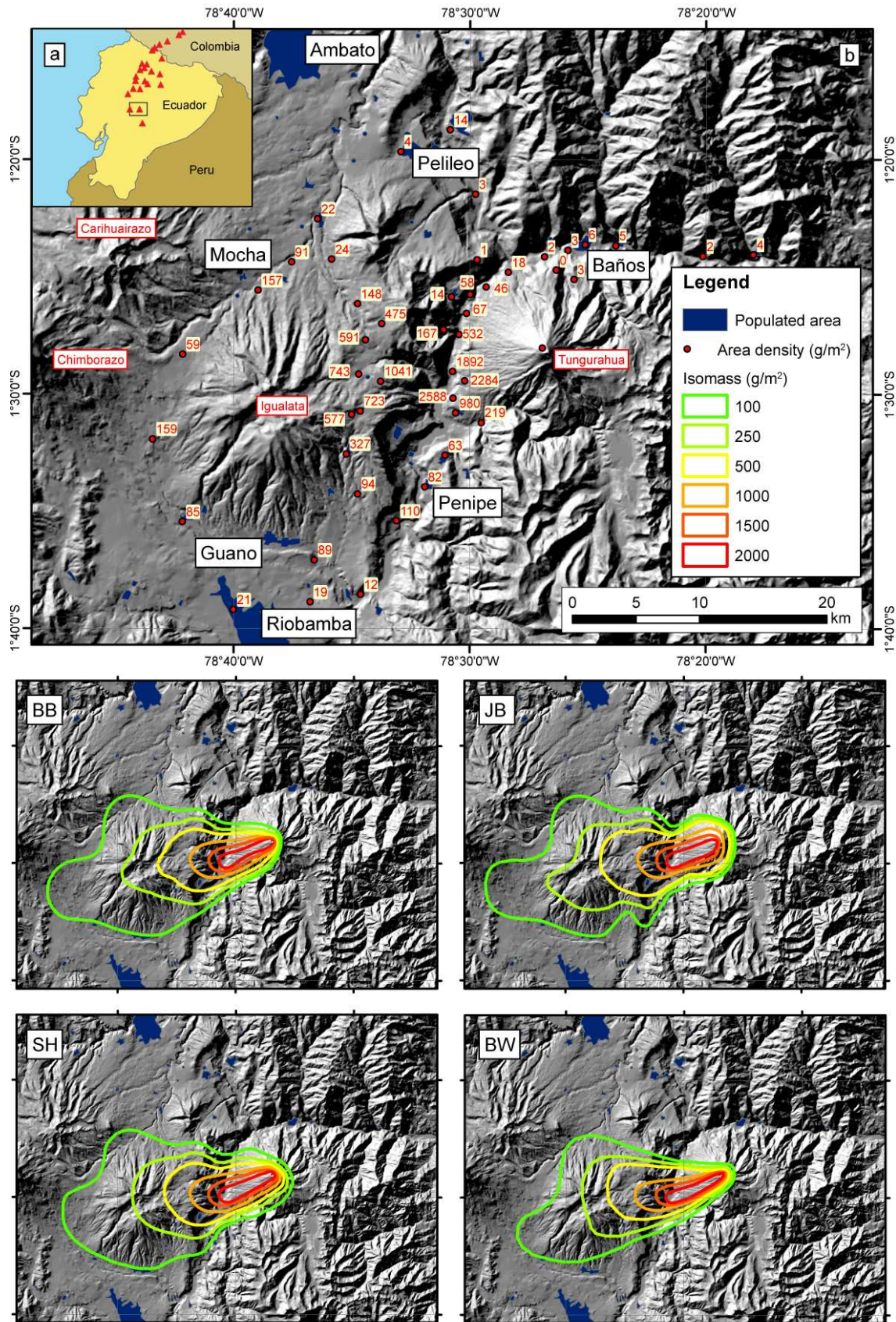


Figure 3: Location map of Tungurahua volcano in the Ecuadorian Volcanic Arc. b. Shaded relief map of the sampling network with the area density value (in g/m²) of the March 2013 Tungurahua eruption. BB, JB, SH, BW: isomass maps named after the initials of the co-authors of this study. In black: names of the main towns of the area. In red: names of the main volcanoes in the area.

sector is clearly the most affected with more than 90% of the days displaying both VAAC alerts and fallout reports. Fallouts were also reported in the WNW, SW and SSW quadrants more than 30% of the days, in agreement with the VAAC alerts. Apparently the northern and eastern sectors were not affected by this eruption.

For both eruptions there is no fallout report in the ESE-SSE sectors due to the absence of volunteers in these regions. However, the Washington VAAC did not report any volcanic plumes in those directions; so no mislead will be introduced in the interpretation of the data.

Field data and isomass maps

For the December 2012 eruption, the calculated area densities range from 22 to 1667 g/m² with a maximum thickness of 1.3 mm measured in El Manzano village. Accordingly, the deposit maps for this eruption were drawn using 100, 200, 400, 800, 1200, and 1600 g/m² isomass values (Figure 2). The March 2013 tephra deposit has a wider range of area densities (0 to 2588 g/m²) with a maximum thickness of 2.0 mm also measured in El Manzano. We chose 100, 250, 500, 1000, 1500, and 2000 g/m² isomass values to draw the deposit maps corresponding to this eruption (Figure 3).

The isomass maps compiled by the four co-authors for the December 2012 eruption vary in fallout dispersal direction. The BB and SH maps have three similar fallout dispersal directions (W, N, and E) while the JB and BW maps have only two (W and E, W and NE respectively). The contours of the isomasses present some discrepancies between the four maps as there are irregular contours in the BB and SH maps and smooth contours in the JB and BW maps (Figure 2). In spite of these aesthetic differences, the area of each isomass in all four maps is relatively similar.

In comparison, the isomass maps for the March 2013 eruption are much more consistent with a single direction of fallout dispersal toward the WSW. The shape and the area of the isomasses are also quite similar, however, the JB map has noticeably irregular contours while the BW map is the smoothest (Figure 3).

Total mass calculation

The semilog plots of area density versus square root of isomass area establish that the data from the maps of both eruptions are equally scattered (Figure 4). The empirical law chosen to calculate the total mass of the fallouts is based on the shape of the data series and the availability of proximal and distal datapoints. The lack of very proximal (< 6 km) and very distal (> 32 km) datapoints makes the use of the power-law formula unsuitable [6]. Additionally, the power-law exponent calculated for all the isomass maps is <2, which is known to produce an even larger uncertainty [14]. Because most of the data series does not permit the identification of one (or more) sharp breaks of slope, we used the single segment exponential law corrected for non-elliptical

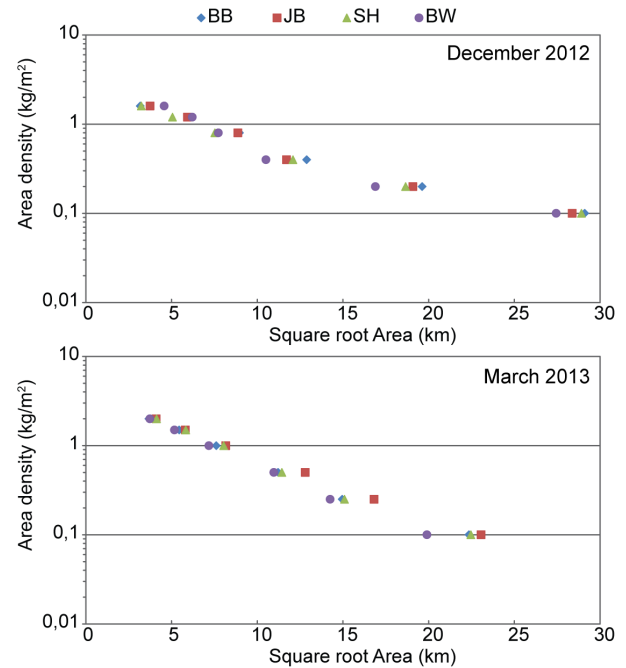


Figure 4: Semilog plots of area density versus square root of isomass area for the December 2012 and March 2013 Tungurahua fallouts. BB, JB, SH, BW: data series corresponding to the isomass maps in Figures 2 and 3.

isomasses [3, 4] and the Weibull function [13] to fit the field data.

The coefficient of determination (R^2) is a statistical parameter used to illustrate the fit between the data series and the empirical law. For both eruptions, the Bonadonna and Costa method [13] gives the best R^2 values (Table 1), which is expected as the Weibull function calculates the best fit regression law based on a range of independent empirical parameters. Good R^2 values are obtained using the Pyle method [3] for the March 2013 eruption while it produced less than ideal results for the December 2012 eruption. It is important to note that excellent R^2 values do not necessarily imply that the total mass calculation is closer to the reality. A simple statistical analysis of the results, using average and standard deviation, reveals that the quantification of the December 2012 eruption has much more scattered values than the March 2013 eruption. The variation on the total mass value reaches 102% for the December 2012 eruption while it reaches only 37% for the March 2013 eruption.

Total volume estimation

Based on the results presented in Table 1, there are different ways to estimate the total mass of Tungurahua fallouts. The March 2013 results display a small scattering of data even between the two empirical methods and, for this reason, we propose to use the full mass range. For the December 2012 eruption the Bonadonna and Costa method [13] appears to better represent the data series so we propose to use only those results with a more selective mass range.

Co-author	December 2012				March 2013			
	Pyle 1989, Fierstein and Nathenson 1992		Bonadonna and Costa 2012		Pyle 1989, Fierstein and Nathenson 1992		Bonadonna and Costa 2012	
	Total mass (10 ⁸ kg)	R ²	Total mass (10 ⁸ kg)	R ²	Total mass (10 ⁸ kg)	R ²	Total mass (10 ⁸ kg)	R ²
BB	3.42	0.977	3.59	0.981	2.56	0.991	2.77	0.994
JB	3.23	0.964	3.90	0.983	2.96	0.998	3.06	0.999
SH	3.19	0.967	3.80	0.993	2.68	0.989	3.01	0.994
BW	2.89	0.925	5.84	0.991	2.23	0.998	2.34	0.999
Average	3.18		4.28		2.61		2.80	
Standard deviation	0.22		1.05		0.30		0.33	
Full mass range	[2.89-5.84] 10 ⁸ kg				[2.23-3.06] 10 ⁸ kg			
Selected mass range	[3.59-5.84] 10 ⁸ kg				[2.23-3.06] 10 ⁸ kg			
Average bulk density	1273±73 kg/m ³ [7]				1314±84 kg/m ³ [12]			
Volume range	[2.82-4.59] 10 ⁵ kg				[1.70-2.33] 10 ⁵ kg			

Table 1: Total mass and volume quantification of the December 2012 and March 2013 Tungurahua fallouts. R²: coefficient of determination. BB, JB, SH, BW: initials of the co-authors of this study. Between []: number of thickness readings used to calculate the average bulk density and its standard deviation.

Bulk densities calculated with thickness measurements for both eruptions gave consistent results and were used to estimate the volume of the tephra fallouts. Using the selected mass range for the December 2012 eruption (3.59-5.84·10⁸ kg) and the average bulk density of the deposit measured in 7 locations (1273 ± 73 kg/m³), the total volume is estimated between 2.82 and 4.59 10⁵ m³. The same estimation was done for the March 2013 eruption (2.23-3.06 10⁸ kg, 1314 ± 84 kg/m³ calculated with 12 thickness readings) and gives a total volume between 1.70 and 2.33 10⁵ m³. According to the total volume of tephra, both eruptions can be qualified as VEI 1 (Volcanic Explosivity index, [1]).

Discussion

Does wind direction variability affect isomass map compilation?

According to Biass and Bonadonna [7], the compilation of isopach (and isomass) maps relies mostly on the quality of the deposit exposure. In our case, the deposit exposure is almost the same between the two eruptions (42 and 47 data point in December 2012 and March 2013 respectively). Furthermore, the use of the ashmeters creates more homogeneous sampling conditions, drastically reducing the influence of weathering processes [12]. Our data clearly establishes that the wind direction was more variable during the December 2012 eruption (W, N, and E) than during that of March 2013 (WSW) (Figure 1). This information can also be partially deduced from the isomass maps (Figure 2 and 3) even with some discrepancies between each co-author's interpretations. The isomass maps from the December 2012 eruptions exhibit a wider variety of main dispersion axes, isomass shape, and roughness. We attribute these features to the difficulty in drawing non-elliptical isomass curves, allowing more subjective interpretations of the field data. Some authors attribute a 10% error to the compilation process [7, 13] but this study affirms

that the wind direction variability must be considered as an important factor in the error estimation.

How does the choice of the empirical method influence the total mass calculation?

The total mass of Tungurahua eruptions has been calculated using two different empirical methods. For the March 2013 fallout the difference between the one segment exponential law and the Weibull function is always around 10%. For the December 2012 eruption this difference increased to more than 100% in some cases. The Pyle method [3], even used with the corrected formula [4], typically underestimates the total mass of the tephra deposit [7] but this trend is amplified in the case of a complex non-elliptical deposit. Therefore, the Pyle method [3] should be used only for preliminary estimates in restricted cases when the wind direction is fairly constant during the eruption. In general, the Weibull function [13] seems to represent better the data series even if the standard deviation for the December 2012 fallout total mass is greater than with the Pyle method [3].

Conclusions

The eruptive plumes of December 2012 and March 2013 from the Tungurahua volcano were affected by different atmospheric currents. The VAAC alerts and IGEPN fallout reports indicate that the December eruptive period displayed a wide variation of wind direction (W, N, and E) while the March episode presented a steady wind direction (WSW). The study of the tephra deposits proves that the variability of the wind direction greatly influences the quantification procedure. In particular, our results highlight that a higher variability of the wind direction during the eruption will produce a greater degree of subjective interpretation of the field data during the map compilation process. This paper also illustrates the sensitivity of some empirical methods to the shape of the deposit maps which can lead to an underestimate

of the fallout volume (or mass). Tephra fallout quantification is a complex procedure based primarily on the interpretation of field data and it should always include a critical analysis of the final results and an estimation of the uncertainty.

Acknowledgements

The authors thank the Universidad San Francisco de Quito for logistic support. We would like to thank the personnel of the Tungurahua Volcano Observatory of the Instituto Geofísico de la Escuela Politécnica Nacional for the help during the field work. The authors also would like to thank the volunteers around Tungurahua volcano for providing the daily information on the tephra fallouts. The authors acknowledge W. Merino for his participation in the collection of field-data. Daniel Andrade is acknowledged for its constructive and thorough reviews.

References

- [1] Newhall, C.; Self, S. 1982. "The volcanic explosivity index (VEI): an estimate of explosive magnitude for historical volcanism". *Journal of Geophysical Research*, 87:1231–1238.
- [2] Suzuki, T. 1983. "A theoretical model for dispersion of tephra". in: D. Shimozuru and I. Yokoyama (eds) *Arc Volcanism: Physics and Tectonics*, Terra Scientific Publishing, Tokyo, 95–116.
- [3] Pyle, M. 1983. "The thickness, volume and grain-size of tephra fall deposits". *Bulletin of Volcanology*, 51:1–15.
- [4] Fierstein, J.; Nathenson, M. 1992. "Another look at the calculation of fallout tephra volumes". *Bulletin of Volcanology*, 54:156–167.
- [5] Bonadonna, C.; Ernst, G.; Sparks, R. 1998. "Thickness variations and volume estimates of tephra fall deposits: the importance of particle Reynolds number". *Journal of Volcanology and Geothermal Research*, 81:173–187.
- [6] Bonadonna, C.; Houghton, B. 2005. "Total grain-size distribution and volume of tephra fall deposits". *Bulletin of Volcanology*, 67:441–456.
- [7] Biass, S.; Bonadonna, C. 2011. "A quantitative uncertainty assessment of eruptive parameters derived from tephra deposits: The example of two large eruptions of Cotopaxi volcano, Ecuador". *Bulletin of Volcanology*, 73:73–90.
- [8] Eychenne, J.; Le Pennec, J.; Troncoso, L.; Gouhier, M.; Nedelec, J. 2012. "Causes and consequences of bimodal grain-size distribution of tephra fall deposited during the August 2006 Tungurahua eruption (Ecuador)". *Bulletin of Volcanology*, 74:187–205.
- [9] Le Pennec, J.; Ruiz, G.; Ramón, P.; Palacios, E.; Mothes, P.; Yepes, H. 2012. "Impact of tephra falls on the Andean communities: The influences of eruption size and weather conditions during the 1999-2001 activity of Tungurahua volcano, Ecuador". *Journal of Volcanology and Geothermal Research*, 217:91–103.
- [10] Bustillos, J. 2010. "Transición del estilo eruptivo durante las erupciones andesíticas en sistema abierto: Contribución al estudio de los depósitos de ceniza del volcán Tungurahua". *Master thesis, Nice Sophia Antipolis University, France*, 48.
- [11] Bustillos, J.; Mothes, P. 2010. "Ash falls at Tungurahua volcano: implementation of systematic ash collection for quantifying accumulated volumes". *Cities On Volcanoes 6 abstract volume, Tenerife, Canary Island, Spain. May 31 - June 4 2010, 2.7-O-07*.
- [12] Bernard, B. 2013. "Homemade ashmeter: a low-cost, high-efficiency solution to improve tephra field-data collection for contemporary explosive eruptions". *Journal of Applied Volcanology*, 2:1–9.
- [13] Bonadonna, C.; Costa, A. 2012. "Estimating the volume of tephra deposits: A new simple strategy". *Geology*, 40 (5):415–418.
- [14] Bonadonna, C.; Costa, A. 2013. "Modeling of tephra sedimentation from volcanic plumes". in: *Modeling Volcanic Processes: The Physics and Mathematics of Volcanism*. CAMBRIDGE: Cambridge University Press, Editors: S.A. Fagents, T.K.P. Gregg, R.M.C. Lopes, in press, ISBN: 9780521895439.