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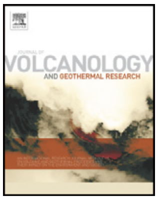

Physical characterization of explosive volcanic eruptions based on tephra deposits: Propagation of uncertainties and sensitivity analysis

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ABSTRACT

Regardless of the recent advances in geophysical monitoring and real-time quantitative observations of explosive volcanic eruptions, the characterization of tephra deposits remains one of the largest sources of information on Eruption Source Parameters (ESPs) (i.e. plume height, erupted volume/mass, Mass Eruption Rate — MER, eruption duration, Total Grain-Size Distribution — TGSD). ESPs are crucial for the characterization of volcanic systems and for the compilation of comprehensive hazard scenarios but are naturally associated with various degrees of uncertainties that are traditionally not well quantified. Recent studies have highlighted the uncertainties associated with the estimation of ESPs mostly related to: i) the intrinsic variability of the natural system, ii) the observational error and iii) the strategies used to determine physical parameters. Here we review recent studies focused on the characterization of these uncertainties and we present a sensitivity analysis for the determination of ESPs and a systematic investigation to quantify the propagation of uncertainty applied to two case studies. In particular, we highlight the dependence of ESPs on specific observations used as input parameters (i.e. diameter of the largest clasts, thickness measurements, area of isopach contours, deposit density, downwind and crosswind range of isopleth maps, and empirical constants and wind speed for the determination of MER). The highest uncertainty is associated to the estimation of MER and eruption duration and is related to the determination of crosswind range of isopleth maps and the empirical constants used in the empirical parameterization relating MER and plume height. Given the exponential nature of the relation between MER and plume height, the propagation of uncertainty is not symmetrical, and both an underestimation of the empirical constant and an overestimation of plume height have the highest impact on the final outcome. A ±20% uncertainty on thickness measurements, area of isopach contours, integration limit for the power-law fit and deposit density result in ESP uncertainties ≤±20% for plume height and erupted volume/mass. Finally, a third case study has also been used to explore the sensitivity of the Voronoi Tessellation strategy for the determination of TGSD and the inversion on both mass/area and grain-size data for the determination of erupted mass and plume height. Results confirm the validity of the methods but also the strong dependence on the distribution and number of observations.

1. Introduction

Description of physical parameters of explosive eruptions is necessary to characterize eruptive behavior of active volcanoes and assess their hazards. Specific physical parameters, such as erupted volume, can help define feeding rates of volcanic systems, understand global volcanic activity and assess eruptive frequency in relation to repose periods. As an example, datasets are available that are devoted to a better understanding of Earth's active volcanoes and that rely on an accurate characterization of eruptive events of the past 10,000 years (e.g. Global Volcanism Program, GVP, http://www.volcano.si.edu/; LaMEVE database, http://www.bgs.ac.uk/vogripa/view/controller.cfc?method=lameve). On the other hand, a range of statistically representative Eruption Source Parameters (ESPs) needs to be determined in order to build comprehensive hazard scenarios for both real-time and long-term hazard assessments of active volcanoes, and, therefore, a large number of eruptions need to be analyzed in detail. ESPs that are required to build hazard scenarios and compile hazard assessments mostly include: column height, Mass Eruption Rate (MER), erupted mass (or volume), eruption duration and Total Grain-Size Distribution (TGSD). Although various strategies have been proposed to assess ESPs, differences exist depending on whether eruptions are observed in real time or reconstructed on the basis of the deposit features. In fact, some ESPs of more recent eruptions are mostly determined based on geophysical monitoring and direct observations (e.g. plume height, eruption onset, eruption duration), while the description of past eruptions typically relies on the characterization of tephra deposits, which are the pyroclastic products that retain the most information of the associated eruptive event. Nonetheless, all

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strategies are affected by various levels of uncertainty that propagates through the various steps required to obtain ESPs. As a result, the quantification of uncertainties associated to key ESPs is crucial to both the characterization of volcanic systems and hazard assessments. This has been addressed by recent studies that have highlighted the importance of a critical characterization of tephra deposits based on a synergy of approaches instead of the application of a single method (Biass and Bonadonna, 2011; Burden et al., 2011, 2013; Le Pennec et al., 2012; Bonadonna and Costa, 2013; Engwell et al., 2013; Klawonn et al., 2014a, b; Maeno et al., 2014). Here we review the main existing strategies commonly used to characterize explosive eruptions based on tephra deposits and we assess uncertainty propagation on two case studies (i.e. 18 May 1980 eruption of Mt St Helens, USA, and Layer 5 of Cotopaxi volcano, Ecuador). We also consider the well-studied tephra deposit of the 1974 eruption of Fuego volcano, Guatemala, to assess the sensitivity of specific strategies to the deposit exposure and distribution of sample points, i.e. Voronoi Tessellation for the determination of TGSD (Bonadonna and Houghton, 2005) and inversion modeling for the determination of erupted mass and plume height.

2. From deposit thickness/mass load to erupted volume/mass

Erupted volume and mass of tephra are typically derived by integrating various empirical functions that fit the measured square root of isopach/isomass contour area versus the logarithm of thickness or mass/area. With a certain level of uncertainty associated with the variation of compactness with distance from vent, erupted mass can also be derived from erupted volume, and vice versa, if the deposit density is known. Given that tephra deposits, in particular fine-grained deposits, are subjected to compaction and density variations with time, mass/area data are typically preferred to thickness data. Compaction can decrease thickness up to 50% in a variable timeframe (Thorarinsson, 1954; Hildreth and Drake, 1992; Guichard et al., 1993; Larsen and Eiriksson, 2008; Engwell et al., 2013). Nonetheless, from a practical point of view, mass/area data are common for the study of real-time small-moderate eruptions, while thickness data remain the most obvious choice for paleo-volcanological studies (e.g. Engwell et al., 2013).

In all cases, the first requirement to study the dispersal of tephra deposits include the choice of i) spacing of sampling sites, ii) number of sampling sites, iii) extent of deposit to be studied, and iv) actual measurement of thickness or mass/area. Natural variance and observational error are difficult to be characterized separately, but observational error was shown to be significantly smaller than the uncertainty related to natural deposit variability. In particular, Engwell et al. (2013) showed how the average uncertainty associated with thickness measurement of the Fogo A Plinian deposit (Azores), accounting for both natural variance and observational error, is about 30%, of which observational error is less than 10% (i.e. one third of the total uncertainty) (Table 1). This is in agreement with the results of Le Pennec et al. (2012) who assessed an average uncertainty of 8% for the thickness contours of the August 2001 tephra deposit of Tungurahua volcano (Ecuador) with a range between 3 and 25% based on 3–8 different thickness measurements performed at individual deposits (Table 1). For the case of Fogo A, such an uncertainty on the thickness measurements led to a volume uncertainty of about 1%, i.e. a volume error of 0.02 km^3 (considering 250 thickness measurements; Engwell et al., 2013). They also showed how, for an eruption of this size, a single measurement is representative of an area between 0.5 and 10 km^2 of deposit. Finally, Klawonn et al. (2014a) showed how the data spacing for the 1959 Kīlauea Iki deposit (small-moderate cone building eruption) did not significantly affect the resulting volume calculations.

The second requirement for the description of deposit dispersal is the compilation of isopach/isomass maps, which typically includes the selection of contour intervals and the actual data contouring that can be done by hand or by using dedicated software. Isopach/isomass maps can then be used to determine erupted volume/mass but also to analyze sedimentation patterns in more detail (e.g. direction of dispersal and presence of multiple lobes, e.g. Etna 2001 eruption (Scollo et al., 2007), and/or multiple maxima of accumulation, e.g. Mt St Helens 1980 eruption (Sarna-Wojcicki et al., 1981)). Klawonn et al. (2014a) found that volume estimates are consistent irrespective of the choice and the degree of smoothing of the contours (75 to 273 measurements). In contrast, Cioni et al. (2011) reported a variation between 9 and 38% in the erupted volume associated with seven units of the 512 AD eruption of Vesuvius based on the calculations of four different volcanologists using the single segment method of Fierstein and Nathenson (1992) (15 to 28 locations). This could be related to the implication that the choice of contours, often complicated by deposit exposure/preservation, has on the extrapolation of the best fit to the most proximal and distal area, as illustrated by Klawonn et al. (2014b). The uncertainty associated with the contour area is also related to the data density. As an example, the area uncertainty for the 1959 Kīlauea Iki tephra deposit is high very far and very close to the volcano (over 30%), but relatively small in medial area (<10%) where data density is higher. Le Pennec et al. (2012) had estimated an average level of uncertainty of about 7% associated with the August 2001 eruption of Tungurahua (Table 1). Finally, Klawonn et al. (2014a) concluded that the smallest contours are what most affected the volume calculation of the 1959 Kīlauea Iki deposit. In fact, the choice of the smallest contours, which are typically based on few data, can have the effect of significantly underestimating the distal fall, confirming the results of Bonadonna and Costa (2013). Bonadonna and Houghton (2005) and Bonadonna and Costa (2012) have also shown how what most influences the volume calculation based on empirical fit (e.g. exponential, power law and Weibull) is the lack of data for specific sections of the deposit (e.g. proximal and/or distal) more than the actual number of data points and contours.

Table 1
Levels of uncertainty associated with the various steps required for the estimation of tephra-deposit volume as reported by various authors (BB: Biass and Bonadonna (2011); BC: Bonadonna and Costa (2012); C: Cioni et al. (2011); E: Engwell et al. (2013); LP: Le Pennec et al. (2012); K: Klawonn et al. (2014b); M: Maeno et al. (2014)): i) thickness measurement (that includes both the natural variation of the deposit and the observational error), ii) data contouring, iii) error associated with the empirical fit of observed thickness and iv) application of empirical integration strategies (i.e. multi-segment exponential and power-law for LP and BB, multi-segment exponential, power-law and Weibull for BC and K, multi-segment exponential, power-law, Weibull, trapezoidal rule and cubic B-spline for M) versus analytical inversion strategies. Thickness ranges for proximal, medial and distal area are indicated in brackets. White cells indicate the data spread, while shaded areas indicate the direct influence of individual parameters on the determination of erupted volume.

	Proximal area	Medial area	Distal area
Thickness measurement	30%$_{E}$		
Observational error	9%$_{E}$		
Observational error	4% (12–4 cm)$_{LP}$	8% (5–0.5 cm)$_{LP}$	21% (0.3–0.2 cm)$_{LP}$
Data contouring	7%$_{LP}$		
Data contouring	15–40%$_{K}$ (>350 cm)	<10%$_{K}$ (5–350 cm)	20–25%$_{K}$ (<5 cm)
Empirical fit	11–99%$_{BC}$		
Integration strategy	53%$_{K}$ (>350 cm)	8%$_{K}$ (5–350 cm)	62%$_{K}$ (<5 cm)
Integration strategy	21–68%$_{BB}$, 4–94%$_{BC}$, 32%$_{LP}$, 25–75%$_{M}$		
Analytical inversion	26–67%$_{BB}$		
Thickness measurement	1.3%$_{E}$		
Data contouring	9–38%$_{C}$		

Uncertainty on volumes estimated from empirical fitting is also introduced by the residuals on observed data. As an example, Bonadonna and Costa (2012) report a variation of the error associated with the empirical fit of observed thickness (i.e. Root Mean Square Error, RMSE) between 11 and 68%, 23 and 99%, and 11 and 59% for the multi-segment exponential, the power-law and the Weibull fitting respectively (Table 1). However, it is important to bear in mind that in some cases the RMSE may appear low because of the paucity of data. In fact, a small dataset can be often better fit than a large dataset even though it is not representative of the actual thinning trend.

A certain spread in volume data is also associated with the different existing strategies that can be applied to derive the volume/mass of the erupted material (Table 1). Most recent strategies are based on the integration of exponential, power-law and Weibull fit of the square