Earth and Planetary Science Letters 443 (2016) 90–107

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Assessing tephra total grain-size distribution: Insights from field data analysis

A. Costa [a,*], L. Pioli [b], C. Bonadonna [b]

[a] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Italy
[b] Department of Earth Sciences, University of Geneva, Geneva, Switzerland

ARTICLE INFO

Article history:
Received 21 November 2015
Received in revised form 9 February 2016
Accepted 19 February 2016
Available online 25 March 2016
Editor: T.A. Mather

Keywords:
tephra dispersal
grain-size distribution
eruption source parameters
magma fragmentation

ABSTRACT

The Total Grain-Size Distribution (TGSD) of tephra deposits is crucial for hazard assessment and provides fundamental insights into eruption dynamics. It controls both the mass distribution within the eruptive plume and the sedimentation processes and can provide essential information on the fragmentation mechanisms. TGSD is typically calculated by integrating deposit grain-size at different locations. The result of such integration is affected not only by the number, but also by the spatial distribution and distance from the vent of the sampling sites. In order to evaluate the reliability of TGSDs, we assessed representative sampling distances for pyroclasts of different sizes through dedicated numerical simulations of tephra dispersal. Results reveal that, depending on wind conditions, a representative grain-size distribution of tephra deposits down to ∼100 μm can be obtained by integrating samples collected at distances from less than one tenth up to a few tens of the column height. The statistical properties of TGSDs representative of a range of eruption styles were calculated by fitting the data with a few general distributions given by the sum of two log-normal distributions (bi-Gaussian in Φ-units), the sum of two Weibull distributions, and a generalized log-logistic distribution for the cumulative number distributions. The main parameters of the bi-lognormal fitting correlate with height of the eruptive columns and magma viscosity, allowing general relationships to be used for estimating TGSD generated in a variety of eruptive styles and for different magma compositions. Fitting results of the cumulative number distribution show two different power law trends for coarse and fine fractions of tephra particles, respectively.

Our results shed light on the complex processes that control the size of particles being injected into the atmosphere during volcanic explosive eruptions and represent the first attempt to assess TGSD on the basis of pivotal physical quantities, such as magma viscosity and plume height. Our empirical method can be used to assess the main features of TGSD necessary for numerical simulations aimed to real-time forecasting and long-term hazard assessment when more accurate field-derived TGSDs are not available.

1. Introduction

Volcanic explosive eruptions are typically studied, characterized, and classified based on physical parameters associated with eruption dynamics and their deposits (e.g. plume height, mass eruption rate, erupted volume, and deposit dispersal). Out of all Eruption Source Parameters (ESPs), the size distribution of tephra at the vent, i.e. all particles injected and dispersed through the atmosphere, commonly defined as Total Grain-Size Distribution (TGSD), retains fundamental information on fragmentation mechanisms (e.g. Kaminski and Jaupart, 1998; Rust and Cashman, 2011) and is crucial to tephra hazard assessments and real-time forecasting (e.g. Folch, 2012). Nonetheless, the determination of TGSD is not straightforward mostly due to *i*) poor exposure of most tephra deposits, with significant areas being often of difficult access, *ii*) variable rate of deposit erosion, *iii*) difficulty to recognise or correlate proximal with distal deposits, *iv*) combination of multiple eruptive styles and processes that complicate the deposit, e.g. co-Pyroclastic Density Currents (PDC) plumes (e.g. Carey and Sigurdsson, 1982), *v*) uncertainties arising from the integration of individual grain-size samples (e.g. Bonadonna and Houghton, 2005; Bonadonna et al., 2015a; Murrow et al., 1980). For these reasons only a few TGSDs are available in the literature, and are often lacking of either or both the fine and the coarse fraction (e.g. Bonadonna and Houghton, 2005; Rose and Durant, 2009; Scollo et al., 2014). The large uncertainties associated with the determination of TGSD, limit our understanding of eruption dynamics

---

[*] Corresponding author.
E-mail address: antonio.costa@ingv.it (A. Costa).

http://dx.doi.org/10.1016/j.epsl.2016.02.040

and significantly affect the simulation of tephra dispersal necessary for hazard assessments and real-time forecasting. In particular, the TGSD has already been shown to represent one of the most critical ESPs, significantly effecting tephra dispersal model outputs (e.g. Scollo et al., 2008; Beckett et al., 2015). Numerical models used for the real-time forecasting of volcanic clouds typically model only the fine-ash fraction of the TGSD (i.e. particles <63 μm) because it is the most relevant for the far-field dispersal and risk mitigation for aviation (e.g. Folch, 2012). Nonetheless, an accurate characterization of the whole size range of erupted particles is necessary to assign the associated mass and describe the mass distribution in the eruptive plume (e.g. Beckett et al., 2015).

Existing models of magma fragmentation commonly assume a threshold criterion for magma fragmentation, simply using a critical vesicularity (Sparks, 1978; Kaminski and Jaupart, 1998), or a critical shear-rate beyond which the liquid magma behaves as a brittle solid (Dingwell, 1996; Papale, 1999), or a critical bubble overpressure (e.g. Melnik, 1999). Fragmentation can occur, in a “brittle-like” fashion, when the characteristic decompression time is larger than the relaxation time (e.g. Kameda et al., 2013). Generally the process is controlled by several factors, such as magma chamber pressure, conduit geometry, gas content and magma surface energy (Macedonio et al., 1994; Dingwell, 1996; Melnik, 1999; Papale, 1999; Costa et al., 2009c). Other key conduit properties, such as magma permeability, shear-rate, and crystallinity, can vary locally due to differential magma velocity, shear heating and crystal resorption, determining non-uniform fragmentation within the conduit or during the eruption (e.g. Costa et al., 2007; Mueller et al., 2008; Polacci et al., 2001).

Other processes, such as comminution due to particle collision above magma the fragmentation level (both within the eruptive jet and within pyroclastic density currents) and water–magma interaction, further increase the complexity of TGSDs (e.g. Wohletz, 1986). Disruption and erosion of the wall–rock enriches the erupted mixture in lithic fragments (e.g. Macedonio et al., 1994; Costa et al., 2009c) with a relative weight fraction that varies significantly with eruptive style, ranging typically from a few to tens of percent in sub-Plinian/Plinian eruptions to 100% in phreatic eruptions (e.g. Bryan et al., 2000). Magma/water explosive interaction can increase such a fraction (e.g. Barberi et al., 1989).

The complexity of magma fragmentation and the interplay of multiple eruptive phases and processes that characterize many explosive eruptions imply that analytical descriptions of TGSDs are difficult to constrain and generalize. Nonetheless, TGSDs represent a crucial input parameter of tephra transport models used to produce long-term hazard assessments and real-time forecasting, and, therefore, an accurate description and discussion of associated uncertainties is necessary. At the moment, although their number is increasing fast, there are still a limited number of reliable TGSD of tephra deposits available in the literature. These data do not have uniform characteristics in terms of number of sampled outcrops, computing techniques, and extent of sampling. Here we select a dataset limited to the most representative distributions, for which statistical analysis was performed to identify complexities and common features and to define statistical models that can be used to describe their general properties. Finally, in order to develop a practical method to estimate TGSDs generated in a variety of eruptive styles and for different magma compositions, we propose an empirical method based on the strongest correlations between the statistical parameters of the best fitting distributions and two parameters routinely assessed relevant to the fragmentation process: the magma viscosity and the height of the eruption column of the main explosive phase of the eruption (that is a function of the mass eruption rate).

Table 1
Normalized distances from the vent of the barycentre of the deposits for different particle diameters representative of lapilli and coarse ash sizes, for deposits from plumes erupted at different latitude and variable wind speeds, as given by numerical simulations. D = distance from the vent along the dispersal axis, H = plume height above vent. Sampling distances normalized to H should be similar to the reported D/H values in the table in order to be representative of sampling the entire spectrum of lapilli and ash. See ESM1 for further details.

Latitude	Wind intensity	D/H		
		$\Phi = -6$	$\Phi = -1$	$\Phi = 3$
Equatorial	Medium	0.05–0.1	0.2–0.5	2–5
Mid-latitude	Low	0.05	0.2–0.3	2–3
Mid-latitude	Medium	0.2–0.3	1–1.4	9–14
Mid-latitude	Strong	0.4–0.5	2–3	17–28
Polar	Medium	0.2–0.3	1.1–1.5	10–15

2. Representativeness of sampling distance and outcrop density

TGSDs are typically reconstructed from the deposit GSD (commonly expressed as wt.% of particles in Φ-classes where the diameter of the particles is $d = 2^{-\Phi}$ mm) measured at single locations and integrated using various techniques. The GSD of particles settled at a given location varies with distance from the vent as it is controlled by wind conditions, column height and particle terminal fall velocity, which is a function of their size, shape, and density.

The reliability of the reconstructed TGSDs strongly depends on sampling spatial distribution and sampling density (Bonadonna et al., 2015a) and numerical models can be used to assess the representativeness of data sampling (e.g. Tsunematsu and Bonadonna, 2015). We carried out a set of numerical simulations to calculate the centre of mass of the deposit (hereinafter barycentre) for particles of any Φ-class leaving the eruptive column from different heights and being affected by different winds at different levels (Macedonio et al., 2008). The minimum sampling distance from the vent for each Φ-class is assumed to be at least equal to the barycentre of that class (i.e. the location where most of the mass of that Φ-class is mainly deposited). If we consider $\Phi = 3$ as the size threshold for particles that settle as an individual particle, i.e. their settling velocity is not altered by aggregation processes and convective instabilities (e.g. Brown et al., 2012; Tsunematsu and Bonadonna, 2015), from simulation results carried out considering different conditions, we can infer that tephra deposits should be sampled up to about 10–60 km for 6–30 km high plumes dispersed in a low wind field (e.g. ∼8 m/s as maximum wind intensity at the tropopause), 45–300 km for 6–30 km plumes transported in a medium wind field (e.g. ∼40 m/s as maximum wind intensity at the tropopause), and 90–650 km for 6–30 km plumes dispersed in a strong wind field (e.g. ∼80 m/s as maximum wind intensity at the tropopause) (see ESM1 for further details). Interesting to notice that for a given wind field, the sedimentation distance normalized with respect to the maximum plume height remains almost constant for coarse particles or varies less than a factor ∼2 for fine particles (Fig. 1, Table 1, ESM1).

Finally, it is also important to highlight that both the method chosen to reconstruct the TGSD and the distribution of outcrops can significantly affect the final outcomes (e.g. Bonadonna and Houghton, 2005). The lack of proximal or distal outcrops due to either erosion/remobilization or inaccessibility of the deposit due to vegetation, urbanization or presence of a lake/ocean can also result in an overestimation or underestimation of the fine fraction, respectively (Bonadonna and Houghton, 2005; Bonadonna et al., 2015a). Therefore, the evaluation of the sampling distance from the vent with respect to the eruptive column height and atmospheric conditions and the distribution of the sampling sites are both necessary to assess the associated representativeness (Bonadonna et al., 2015a; Tsunematsu and Bonadonna, 2015). It is also worth