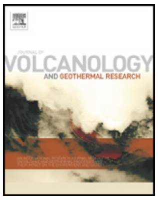
Journal of Volcanology and Geothermal Research 301 (2015) 191–203

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores



Grain-size distribution of volcaniclastic rocks 2: Characterizing grain size and hydraulic sorting

Martin Jutzeler [a,*], Jocelyn McPhie [a], Sharon R. Allen [a], A.A. Proussevitch [b]

[a] CODES – ARC Centre of Excellence in Ore Deposits, University of Tasmania, PO Box 79, Hobart 7005, Australia
[b] Earth Systems Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, United States

ARTICLE INFO

Article history:
Received 1 August 2014
Accepted 19 May 2015
Available online 28 May 2015

Keywords:
Stereology
Hydraulic sorting
Grain size distribution
Volcaniclastic rock
Ohanapecosh
Dogashima

ABSTRACT

Quantification of the grain size distribution of sediments allows interpretation of processes of transport and deposition. Jutzeler et al. (2012) developed a technique to determine grain size distribution of consolidated clastic rocks using functional stereology, allowing direct comparison between unconsolidated sediments and rocks. Here, we develop this technique to characterize hydraulic sorting and infer transport and deposition processes. We compare computed grain size and sorting of volcaniclastic rocks with field-based characteristics of volcaniclastic facies for which transport and depositional mechanisms have been inferred. We studied pumice-rich, subaqueous facies of volcaniclastic rocks from the Oligocene Ohanapecosh Formation (Ancestral Cascades, Washington, USA), Pliocene Dogashima Formation (Izu Peninsula, Honshu, Japan), Miocene Manukau Subgroup (Northland, New Zealand) and the Quaternary Sierra La Primavera caldera (Jalisco State, Mexico). These sequences differ in bed thickness, grading and abundance of matrix. We propose to evaluate grain size and sorting of volcaniclastic deposits by values of their modes, matrix proportion (<2 mm; F-1) and D_{16}, instead of median diameter (D_{50}) and standard deviation parameters. F-1 and D_{16} can be uniformly used to characterize and compare sieving and functional stereology data. Volcaniclastic deposits typically consist of mixtures of particles that vary greatly in density and porosity. Hydraulic sorting ratios can be used to test whether mixed clast populations of pumice and dense clasts are hydraulically sorted with each other, considering various types of transport underwater. Evaluation of this ratio for our samples shows that most studied volcaniclastic facies are deposited by settling from density currents, and that basal dense clast breccias are emplaced by shear rolling. These hydraulic sorting ratios can be applied to any type of clastic rocks, and indifferently on consolidated and unconsolidated samples.

1. Introduction

The interpretation of mechanisms of transport and deposition for detrital sediments has been in use for at least five decades, and relies on field characteristics, grain size and sorting (Friedman, 1962; Kuno et al., 1964; Passega, 1964; Visher, 1969; Buller and McManus, 1973; Glaister and Nelson, 1974; Garzanti et al., 2009). In addition, variations in grain size distribution, sorting and componentry of pyroclastic deposits with distance from source are important attributes used to constrain models of subaerial explosive eruptions and volcaniclastic density currents (e.g. Walker, 1971; Sparks et al., 1973; Sparks, 1976; Walker, 1983, 1984; Wilson and Walker, 1985; Carey, 1991; Bonadonna and Houghton, 2005; Dufek and Bergantz, 2007; Macedonio et al., 2008; Volentik et al., 2010; Alfano et al., 2011; Mackaman-Lofland et al., 2014). Sorting and grading are two critical values from which inferences can be made on processes of transport and deposition.

Furthermore, these grain-size based physical models of transport and deposition have not been applied to lithified and/or welded deposits, although these rocks are far more abundant on Earth than unconsolidated deposits. We apply the image analysis and functional stereology technique using predefined distribution functions (Proussevitch et al., 2007a, 2007b) adapted for (consolidated) clastic rocks (Jutzeler et al., 2012) for assessing the grain size characteristics of subaqueous volcaniclastic facies, which are mostly lithified and commonly contain less fines than their subaerial analogs. In this paper, we refer to this technique as functional stereology as it implicitly combines statistical functions with earlier formulations of stereological transformations (Sahagian and Proussevitch, 1998). The grain size distribution of the samples studied in this paper was calculated as following a log-normal behavior, as does a large selection of natural object sizing categories (Proussevitch et al., 2007a, 2007b). Following formulations from our previous work (Jutzeler et al., 2012), we use normal (Gaussian) continuous distribution for clast sizes in phi (ϕ) units (Krumbein, 1936) as the predefined function, equivalent to log-normal distribution with respect

---

* Corresponding author at: National Oceanography Centre, Southampton, European Way, Waterfront Campus, Southampton, SO14 3ZH, United Kingdom. Tel.: +44 23 80596 559.
E-mail address: jutzeler@gmail.com (M. Jutzeler).

http://dx.doi.org/10.1016/j.jvolgeores.2015.05.019

to linear units (e.g. meters). Assumed conformity of 2D (cross-section areas) and 3D (volumes) distribution functions will be researched in our future studies.

Previous work on use of grain size distribution to infer depositional processes include Visher (1969) and Glaister and Nelson (1974), who proposed a classification of multi-modal distributions based on the segmentation pattern of cumulative curves and histograms of grain size distribution on unconsolidated deposits. Their method was designed to discriminate among three major types of transport (traction, saltation, suspension), but could be applied only to certain types of detrital sediments (Sengupta et al., 1991), and has not been tested on volcaniclastic deposits. Wohletz et al. (1989) proposed the sequential fragmentation/transport model, which deconvolutes grain size distribution curves into sub-population modes, allowing inference on complex fragmentation and transport histories.

The median and standard deviation of grain diameters in unconsolidated deposits are the parameters most widely used to infer transport and depositional processes for volcaniclastic deposits (Murai, 1961; Walker, 1971, 1983, 1984). Some of these parameters can be directly applied to clastic rocks, but fine components are, in most cases, not resolvable. There is a major issue in comparing median values, as they are dependent on the studied range, and are commonly wrongly applied to multimodal distributions (Folk, 1980). We find the use of mode and D_{16} (Inman, 1952) as more meaningful parameters, and introduce F-1, the ratio of matrix (anything <2 mm).

The mechanisms of transport for subaqueous volcaniclastic density currents are poorly understood in comparison to their siliciclastic homologues (Manville et al., 1998; White, 2000; Manville et al., 2002; Freundt, 2003; Manville and Wilson, 2004; Allen and Freundt, 2006; Talling et al., 2012), as they commonly contain coarse clasts of varying density (pumice or scoria), which are much less dense than conventional dense (i.e. non to poorly-vesicular) clasts. Hydraulic sorting refers to sorting of clasts during transport in a fluid with non-negligible drag. The terminal velocity of a clast in motion in a fluid is dependent on the viscosity and density of the fluid, and of the size, bulk density and shape of the clast (e.g. Rubey, 1933; Clift et al., 1978; Komar and Reimers, 1978; Sallenger, 1979; Komar et al., 1984; Cashman and Fiske, 1991; Kano, 1996; Crowe et al., 1998; Manville and Wilson, 2004; Dellino et al., 2005; Burgisser and Gardner, 2006). Hydraulic equivalence refers to the condition where clasts differing in size and density are deposited similarly (Burgisser and Gardner, 2006).

In this paper, the grain size distribution of coarse (>2 mm) fraction of volcaniclastic rocks deposited underwater is statistically reconstructed by image analysis and functional stereology, using photographs of outcrops and scans of rock slabs (Jutzeler, 2012; Jutzeler et al., 2012). We explore grain size characteristics in terms of modal grain size distribution, matrix ratio, and statistical parameters such as median (D_{50}), D_{16}, and standard deviation. We propose the degree of hydraulic sorting of pumice with dense clasts to infer the original pumice vesicularity and test field-based interpretations of the main transport and depositional processes underwater, including fall, saltation, and various types of rolling, adapting the equations of Burgisser and Gardner (2006) to underwater conditions. This research is novel in using simple ratios to evaluate the subaqueous transport processes for consolidated or unconsolidated deposits composed of clasts with variable density. Our method can be applied to any clastic rock or sediment, using grain size data from various methods (e.g. sieving, laser diffraction, functional stereology), thus widely applicable in sedimentology and volcanology-oriented studies.

1.1. Rock suites

Image analysis and functional stereology were performed on a statistically significant sample suite comprising 85 volcaniclastic samples selected from different origins and from several localities. Most samples belong to the Pliocene Dogashima (Izu Peninsula, Japan) and Oligocene Ohanapecosh (Ancestral Cascades, USA) formations (Fiske, 1963; Cashman and Fiske, 1991; Jutzeler, 2012; Jutzeler et al., 2014a, 2014b). Additional samples were collected in the Miocene Manukau Subgroup (Northland, New Zealand; Allen et al., 2007; Jutzeler, 2012) and in the Quaternary Sierra la Primavera caldera (Jalisco State, Mexico; Clough et al., 1981). The computed grain size data are based on 165 images and are combination of up to three size-nested datasets from outcrop photographs and rock slab scans taken at different magnifications (Jutzeler et al., 2012). Size-nesting in coarse (>2 mm) clast distributions is simpler than for μm-to-mm-sized vesicles in pyroclasts (e.g. Shea et al., 2010), because coarse clasts are commonly relatively homogeneously distributed, and their shape is relatively equant. In addition, we do not consider fine grains in this study. However, high-precision image analysis is complex, as clasts touch others, and clast types, fabric, and color vary substantially among samples.

1.2. Clast componentry

Clastic rocks may contain one or multiple types of clasts (>2 mm), matrix, interstitial pore space and cement. The clast types in the samples analyzed are grouped into two categories for simplicity: 1) Pumice clasts, which contain ~60–90 vol.% of vesicles; some have been compacted to form fiamme. "Deflattening" of the fiamme (Jutzeler et al., 2012) could not be carried out in these examples because the fiamme and pumice clasts coexist in some facies and the original pumice clast vesicularity is unknown. Fiamme only occur in some beds of the Ohanapecosh Formation and are assumed to not substantially modify these data. The density of waterlogged pumice clasts is assumed to range between 1100 and 1600 kg/m^3, corresponding to 60–95 vol.% vesicularity of a waterlogged clast with density of 2500 kg/m^3 at dense rock equivalent. 2) Dense (non-vesicular) clasts and hydrothermally altered clasts; densities for these clasts are assumed to have been 2500 kg/m^3, corresponding to rocks of intermediate composition.

1.3. Matrix cut-off

The original texture of fine grained particles, typically <2 (>−1 ϕ) in clastic rocks, is commonly destroyed or poorly preserved, or difficult to resolve. In eruption-fed volcaniclastic facies, sub-mm clasts generally have the same composition in the coarse clasts, and are likely to be a continuation of the coarse modal clast populations. Two millimeters is a critical boundary that separates sand from gravel, sandstone from breccia or conglomerate, ash from lapilli, and tuff from pyroclastic breccia in clastic deposits (Wentworth, 1922; McPhie et al., 1993; Blott and Pye, 2001; White and Houghton, 2006), thus 2 mm is used in this study to distinguish between clasts and matrix. Hereafter, we keep loose definition for grains and particles, which can be fine (<2 mm) or coarse (>2 mm). For simplicity all particles <2 mm, filling or void are called matrix in this study even though cement and porosity might also be present. Cement is a post-depositional, chemical and/or biochemical precipitate that may partly or completely fill the porosity left between particles that constitute the sediment (matrix and/or clasts). In a rare case (Manukau Subgroup), cement could be separated from matrix, and this sample is clearly identified (Fig. 1).

2. Quantification of textural characteristics in volcaniclastic beds

2.1. Clast volume

Stratigraphic logs are commonly based on visual estimates in the field, and reproduce the main textural characteristics including approximate mean and maximum grain size. The image analysis method (Jutzeler et al., 2012) quantifies clast and matrix volumes (Figs. 1, 2). Data extracted from image analysis give a large choice of parameters on which to characterize and classify clastic aggregates. One of the