Physics and Chemistry of the Earth 45–46 (2012) 33–39

Contents lists available at SciVerse ScienceDirect

Physics and Chemistry of the Earth

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

Abrasion in pyroclastic density currents: Insights from tumbling experiments

Ulrich Kueppers *, Constanze Putz, Oliver Spieler, Donald B Dingwell

Earth & Environmental Sciences, Ludwig Maximilian University, Munich, Germany

ARTICLE INFO

Article history:
Available online 21 September 2011

Keywords:
Pyroclastic density currents
Granular flows
Abrasion
Volcanic ash generation

ABSTRACT

During granular mass movements of any kind, particles may interact with one another. The degree of interaction is a function of several variables including; grain-size distribution, particle concentration, density stratification and degree of fluidisation. The impact of particle interaction is additionally influenced by the relative speed, impact angle and clast temperature. Thus, both source conditions and transport-related processes are expected to influence the flow dynamics of pyroclastic density currents and their subsequent deposition. Here, we use tumbling experiments to shed light on the susceptibility of porous clasts to abrasion.

We investigated the abrasion of unaltered volcanic rocks (5.7–80 vol.% porosity) from Unzen (Japan), Bezymianny (Russia) and Santorini (Greece) volcanoes as well as one synthetic analogue material, an insulating material with the trade name Foamglas® (95 vol.% porosity). Each experiment started with angular fragments generated in a jaw crusher from larger clasts. Two experimental series were performed; on samples with narrow and broader grain-size distributions, respectively. The dry samples were subject to rotational movement at constant speed and ambient temperature in a gum rotational tumbler for durations of 15, 30, 45, 60 and 120 min. The amount of volcanic ash (particles <2 mm) generated was evaluated as a function of experimental duration and sample porosity. We term "abrasion" as the ash fraction generated during the experiments.

The observed increase of "abrasion" with increasing sample porosity and experimental duration is initially non-linear but becomes linear for experiments of 30 min duration or longer. For any given sample, abrasion appears to be more effective for coarser samples and larger initial mass. The observed range of ash generated in our experiments is between 1 and 35 wt.%. We find that this amount generally increases with increasing initial clast size or increasing breadth of the initial grain-size distribution.

Despite the limits in the complexity that is experimentally attainable in this simulation of ash generation, our results clearly testify the rapid and efficient generation of ash by abrasion, strongly influenced by the material properties (*e.g.*, crystallinity, pore textures).

1. Introduction

Primary volcanic deposits may contain juvenile fragments generated by a variety of processes. The strain-rates accompanying the stress- (volume and shear) and temperature-path experienced by magma/lava before its final deposition may range from very low rates (*e.g.*, during dome growth) to very high rates (*e.g.*, during rapid ascent in the conduit or as a gas-pyroclast mixture after fragmentation). All processes affecting magma/lava prior to the cessation of strain and transport can be considered primary processes in the generation of volcanic rocks (Dingwell et al., this issue). Accordingly, processes occurring in pyroclastic density currents (PDCs) can be seen as part of a suite of primary processes that convert (in this case) lava into pyroclasts.

Magmatic fragmentation in the conduit, conventionally viewed as fuelled by overpressure of magmatic volatiles in vesicles, is a very efficient process of pyroclast formation (Alidibirov and Dingwell, 2000; Spieler et al., 2004). It is capable of generating very fine ash (Kueppers et al., 2006) even without the addition of external energy sources such as water. Irrespective of the eruption intensity, fall deposits of explosive eruptions (from proximal basaltic scoria to pumice clasts from plinian eruptions) and experimentally-generated pyroclasts (Spieler et al., 2003) both exhibit characteristic angular clast shapes, indicating that particle abrasion in the ascending gas-pyroclast flow (both in the conduit and in the eruptive column), as well as during fallout, is minor.

Explosive volcanic eruptions also generate PDCs (generally defined as gravity flows with variable particle load) travelling down the flanks of the volcano. Their origin may include *e.g.*, direct blast (Voight et al., 1983), fountain collapse (Varley et al., 2010) or dome collapse (Nakada et al., 1999). As a consequence, PDCs may exhibit significant variations in particle sizes, particle concentration and

* Corresponding author.
E-mail address: u.kueppers@lmu.de (U. Kueppers).

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doi:10.1016/j.pce.2011.09.002

temperature of emplacement and yield a plethora of distinct deposit types (Douillet et al., submitted for publication).

In PDCs, clast interaction is probably the rule rather than the exception (*e.g.*, Branney and Kokelaar, 2003, page 29). Initially heterogeneous clast loads, subjected to clast interaction, have the potential to alter the initial grain-size distribution. In doing so they may affect the subsequent flow behaviour of the currents and thereby influence the nature of the related deposits. Rounded clasts in deposits from PDCs have been attributed to surface rounding (abrasion) and/or grain-size reduction (disruption) with subsequent abrasion at the newly formed edges (*e.g.*, Calder et al., 2000; Belousov et al., 2002; Druitt et al., 2002). Most abrasion has been assumed to result from frictional (rolling bed) and collisional (saltation) processes (Dufek and Manga, 2008).

To date, the systematic investigation of abrasion has been carried out by clast analysis of natural deposits and by laboratory experiments. Freundt and Schmincke (1992) quantified abrasion by measuring the thickness of rinds of bubbly glass around phenocrysts in fall and PDC deposits of the Laacher See eruption (Germany). Taddeucci and Palladino (2002) investigated the correlation of size, density and shape within fall- and PDC-deposits of the Latera Volcanic Complex (Italy). Schwarzkopf et al. (2007) performed impact experiments (constant fall-height) using Merapi (Indonesia) dome rocks and quantified the rate of volcanic ash formation (up to 70 wt.%) as a function of experimental temperature (25–850 °C). Dufek and Manga (2008) propelled single pumice clasts onto each other at room temperature and measured the mass difference before and after the experiment. They found a sharp but non-systematic increase in "ash generation" at impact velocities above 20 m/s and explained this with sample heterogeneities (see also Gravina et al., 2004). Cagnoli and Manga (2004) used a rotational disc below a confined bed of pumice clasts to understand the development of a velocity gradient and the degree of abrasion. At constant experiment duration (1 min), initial grain-size (9,5 > x > 8 mm) and sample mass (100 g), they found a linear relationship between the amount of ash generated and the flow speed in the disc reference frame. Manga et al. (2010) compared natural clasts from PDC deposits and experiments on porous clasts and defined an automated image analysis procedure to describe the degree of clast roundness. Their experiments had a fixed number of starting clasts, constant rotational speed and lasted for up to 3 h. They identified a rough but generally linear correlation of the amount of ash generated with experiment duration. Attal and Lavé (2009) experimentally investigated pebble abrasion during fluvial transport and found a linear correlation between abrasion (attrition) and transport stage.

Despite the number of studies listed above, our understanding of abrasion due to clast interaction and the impact of fine material on flow and depositional behaviour of PDCs remains incomplete. Controlled experiments which encompass the diversity of conditions and processes extant in PDCs in nature are challenging. In order to complement our understanding of these processes, we have performed abrasion experiments investigating the influence of initial sample mass and sample properties on abrasion.

2. Abrasion experiments

In this study, 58 experiments were performed at room temperature and dry conditions in a gum rotational tumbler (r = 50 mm, length 100 mm) with a horizontal rotation axis (Fig. 1). Each experiment started with freshly crushed sample material. At constant rotational speed (40 rpm) and direction, experiment durations between 15 and 120 min translate into a transport distance (x) between 232 and 1857 m, using the following equation:

$$x = l * t * v \quad (1)$$

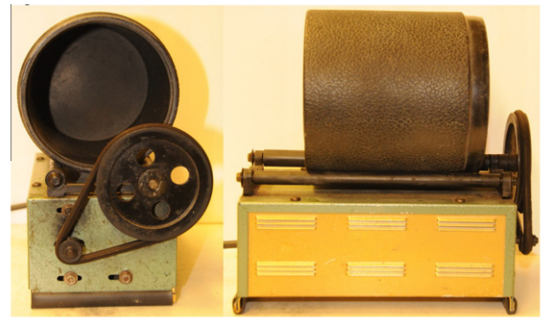

Fig. 1. Pictures of the experimental apparatus taken: (a) parallel and (b) perpendicular to the rotation axis (note that the magnification of the right picture is larger than in the left one.). The cylindrical sample chamber (10 cm long, 10 cm diameter) is rotating in an anti-clockwise direction at constant speed (40 rpm).

with l being the inner circumference of the cylindrical sample chamber (= $2 * \pi * r$), t the experiment duration and v the rotational speed.

During these experiments, particles were constantly rolling inside the rotating, cylindrical sample chamber and interacting with each other by friction (particles sliding by past each other) or impact (particle saltation). The amount of abrasion due to particle-sample chamber interaction is assumed to be negligible due to the small mass of single clast as well as the smooth surface of the gum chamber. The collision speeds and internal pressures generated are estimated to be at the lower end of values expected in natural flows. As sample chamber material and rotational speed are constant, these experiments provide a window into the effect of the physical sample properties on abrasion. The main particle movement mode during the experiments is expected to be closer to conditions in the basal part of PDCs with a high particle concentration.

We performed two sets of experiments: The first set (Table 1) was performed on four porous rock varieties (5.7, 20.5, 35.5 and 53.5 vol.% porosity) from Unzen volcano, Japan. We used a fixed amount of clasts of narrow grain-size distribution (80–100 clasts for experiments with initial size between 8 and 11.2 mm size [-3.0Φ,] and 40 clasts for initial size between 11.2 and 16 mm [-3.5Φ], (termed below, fine and coarse, respectively). The experimental durations were 15, 30, 45, 60 and 120 min. In a second set (Table 2), an initial mass (50.7 and 100 g, respectively) was used together with a broader grain-size distribution (2 < x < 11.2 mm with -3.5Φ:12.2 wt.%; -3.0Φ:20.7 wt.%; -2.5Φ:22.7 wt.%; -2.0Φ:17.8 wt.%; -1.5Φ:13.8 wt.%; -1.0Φ:12.8 wt.%.). We used three different rock types; from Unzen (35.5 vol.% porosity), Bezymianny (61.5 vol.%) and Santorini (80 vol.%) volcanoes as well as Foamglas® (95 vol.%). The latter was used as analogue material as it does not contain crystals and has a highly homogeneous pore structure. Experimental durations were 30, 45, 60 and 120 min, for an initial mass of 50.7 g, and 60 and 120 min for an initial mass of 100 g. In the case of Foamglas® experiments, we used only 25.2 g of initial mass in order to avoid inhibition of the movement of individual clasts inside the tumbler due to close-packing. After each experiment, we collected the entire sample and evaluated the grain-size distribution by dry sieving (at half-Φ steps).

3. Sample characterisation

Sample porosities have been calculated from clast (solid fraction plus voids, i.e., vesicles and fractures) and groundmass (solid fraction without voids) density. Clast density was constrained measuring the mass of single clasts in air and under water (always inside an evacuated plastic bag) following the Archimedean princi-