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Towards fast and routine analyses of volcanic ash morphometry for eruption surveillance applications

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ABSTRACT

The morphometry of volcanic ash produced by explosive eruptions yields ample information on fragmentation processes (e.g. magmatic vs magma–water interactions), and on transport and sedimentation mechanisms. Most previous works on volcanic clast morphometry focused on the Apparent (2D-)Projected shape of ASH grains, here termed APASH, to infer processes and eruptive styles. However, textural analyses of ash grains has remained a long and tedious task that made such approaches inappropriate for eruption surveillance duties. In this work we show that new technological advances on automated dispersion of granular materials imaged with a camera-coupled microscope and enhanced computer capabilities enable fast and high resolution image acquisition of thousands of ash grains that resolve this limitation. With a morpho-grainsizer designed for such fast and routine measurements we perform a series of APASH analyses on selected ash fractions of tephra deposits from known eruptive styles. We record the size, aspect ratio, circularity and convexity of APASH images and assess resolution, reproducibility, minimum population size, and total analytical duration, and offer recommendations for the reporting of APASH data for inter-laboratory comparisons. To avoid fractal geometry concerns, our analyses are carried out at constant size range (250–300 μm) and optical magnification (×5) on ~3000 grains per samples collected from homogenized samples. Results from the andesitic 1999-ongoing eruption of Tungurahua volcano (Ecuador) show that ash particles from the moderate 2001 phase are relatively equant and convex in shape, while the stronger 2006 subplinian phase produced ash grains with more elongated, less circular and less convex APASH signatures. Ash grains from a basaltic scoria cone-forming eruption show even more ragged APASH characteristics. Overall, our protocol allows obtaining accurate and reproducible morphometric measurements that reveal subtle variations of the morphological signature, and the short duration (1.8 hours) of the whole analytical process renders high resolution analyses of ash shape achievable for volcano surveillance applications. This research ultimately aims to set up a morphometric database of APASH results for well-defined eruptive styles, in order to interpret on a short term basis any APASH data from active volcanoes for monitoring purposes.

1. Introduction

Volcanic ash are small (<2 mm) solid particles produced by explosive volcanic eruptions and their study has received increasing attention in recent decades because ash particles may impact the health of populations and pose substantial concerns on air navigation, agriculture, water and electrical supply systems etc. (e.g. Casadevall, 1994; Horwell and Baxter, 2006; Le Pennec et al., 2012; Wardman et al., 2012). On the other hand, volcanic ash particles offer ample information (composition, size range, texture, componentry etc.) on eruption dynamics and styles. For example the mineralogical and geochemical composition yield relevant constraints on magma chamber and conduit processes (e.g. Miwa et al., 2009, 2013; Schiavi et al., 2010; Wright et al., 2012), while data on grain-size distribution (GSD) and componentry assemblages (i.e. proportions of juvenile, accessory and accidental clasts, and free crystals) have proved useful to constrain the size and style of past and modern eruptions (Rose et al., 1973; Scott and McGimsey, 1994; Rivera et al., 2014). In addition, the morphology of ash grains has been examined to investigate transport processes in the volcanic plume (e.g. Riley et al., 2003; Durant et al., 2009; Mele et al., 2011; Klawonn et al., 2014), and more commonly to infer fragmentation mechanisms and styles of the parent eruptive activity. This latter approach has been used for past eruptions to discriminate purely magmatic processes from magma–water interactions processes (e.g. Dellino and La Volpe, 1996a; Büttner et al., 1999; Ersoy et al., 2007; Cioni et al., 2008; Jordan et al., 2014 and references therein). The potential of using volcanic ash characteristics to follow up ongoing eruptions has arisen only recently in the literature: e.g. the presence of glassy juvenile ash grains

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in the deposits of early phreatic outbursts has been interpreted as precursory signals of oncoming magmatic eruptions (e.g. Watanabe et al., 1999; Cashman and Hoblitt, 2004; Suzuki et al., 2013), while ash textures have allowed inferences on magma discharge rates and eruption dynamics (e.g. Taddeucci et al., 2002; Andronico et al., 2009; Miwa et al., 2009; Schiavi et al., 2010; Wright et al., 2012; Eychenne et al., 2015). This information is particularly useful at open-vent volcanic systems where short-lived hazardous paroxysm may occur, in both basaltic (e.g. Etna, Stromboli, Kilauea) (Taddeucci et al., 2002; Andronico et al., 2009; Schiavi et al., 2010; Eychenne et al., 2015) and andesitic contexts (e.g. Colima, Merapi, Sakurajima, Tungurahua) (Savov et al., 2008; Yamanoi et al., 2008; Wright et al., 2012; Eychenne et al., 2013 and references therein). Obtaining rapid, reliable and comprehensive analyses of ash particle characteristics is thus potentially relevant for the surveillance of explosive volcanoes worldwide and the advantage of studying volcanic ash for monitoring purposes is threefold. First, ash particles are solid fragments that are preserved for sampling for some times after the eruption (in contrast to volatiles that are rapidly dispersed). Secondly, volcanic ash can be collected at a safe distance from active vents, avoiding unnecessary approach close to dangerous erupting volcanoes (as can be the case during maintenance of seismic and geodetic instruments). Thirdly, high-quality ash samples can be collected when the erupting volcano is cloudy, using simple collecting devices (e.g. Bernard, 2013; Shimano et al., 2013) or no collectors at all (e.g. uncontaminated ash deposits in snow layers; Scott and McGimsey, 1994; Wallace et al., 2013). While grain-size and componentry data have proved useful to interpret the style of ongoing eruptions (see above references), little attention has been paid to using morphological analyses of ash grains for surveillance applications, because many analytical issues of ash shape characterization are still unresolved. In fact, obtaining fast, high-resolution and reproducible morphological data remains a major challenge that has been rarely addressed in the volcanological literature (e.g. Taddeucci et al., 2002; Andronico et al., 2009; Lautze et al., 2012; Miwa et al., 2015). Notably, previous works have involved uneven sample sizes (i.e. number of grains used to determine average morphological characteristics), dissimilar optical resolution, and different shape parameters that all make rigorous inter-laboratory comparisons ineffective. Working toward standardized ash shape analysis protocols is thus a necessary step to use the morphometry of ash as a robust and reliable tool to determine eruptive styles for monitoring goals. Here we define a morphological signature as a combination of morphological parameters that describes the shape of a single grain or grain population.

The present note is a contribution towards achieving such a goal. Below we summarize some central backgrounds on approaches previously used to characterize the shape of volcanic ash particles and we identify chief issues that require standardization for rapid and effective ash shape characterization and inter-laboratory comparisons. Using a convenient device, we then propose a suitable analytical protocol that allows fast and routine measurements of the size and morphology of ash particles to obtain key morphometric data in a short time, as is required for surveillance applications. We concentrate on the fundamentals of the technique, notably on sample selection and preparation, image acquisition and filtering, and basic morphological analyses. This allows us to illustrate the shape diversity of selected samples collected from three deposits of ongoing and past eruptions, but we focus neither on specific statistical processing issues, such as discriminant analyses of complex object assemblages, nor on detailed volcanological implications of the data provided below (to be presented elsewhere). Our discussion highlights the advances offered by this protocol when compared to previous approaches, and points out its potentials for research and volcano monitoring purposes. The ultimate objective of this work is to set up a comprehensive ash shape database (in which the main eruptive styles are described by selected morphological parameters) that could be used for surveillance in the context of ongoing eruptions.

2. Background on shape analyses of volcanic clasts

2.1. Summary of previous studies

The shape of small volcanoclastic products is highly size-dependent and reflects a diversity of fragmentation, transport and sedimentation processes. Therefore, in order to infer parent eruptive styles, different approaches have been used to characterize the morphology of the clasts. For instance, naked-eye and binocular examinations of thin Pelé's hair reveal their extremely elongated shapes and smooth surfaces that are typical of basaltic Hawaiian eruptive styles. Conversely, Scanning Electron Microscopy (SEM) imaging of equant and blocky ash grains with flat cracked surfaces that meet along acute ridges are commonly attributed to magma water–interactions, e.g. associated with Vulcanian and Surtseyan eruptions (e.g. Heiken and Wohletz, 1985; Büttner et al., 1999). Accordingly, early descriptions of ash grain morphologies have pinpointed features of volcanic ash surface texture and shape that correlate to fragmentation processes and eruptive styles and, to some extent, to transport and sedimentation mechanisms (e.g. Wohletz, 1983; Heiken and Wohletz, 1985; Taddeucci and Palladino, 2002). Such pioneering works, however, lacked a quantitative approach to track the details of complex processes that occur during explosive volcanic eruptions. Later works in the nineties onwards have addressed this limitation through technical advances in microscopy and image analysis sciences that allowed quantitative data to be obtained. After early innovative works using shape descriptors of volcanic clasts (for instance in granulated submarine basaltic rocks, e.g. Honnorez and Kirst, 1975), most previous studies have concentrated on the 2D projected area of particles to quantitatively describe grain shapes (Dellino and La Volpe, 1996a; Riley et al., 2003; Durant et al., 2009; Coltelli et al., 2007; Cioni et al., 2008, 2014; Jordan et al., 2014, and references therein). In this approach it is assumed that the projected 2D outline of the ash particles mirrors three-dimensional (3D) features of volcanic clast shape, which are controlled by bubble size, form and number density, by crystal content and forms, and by deformation-driven and fracturing structures of the interstitial glass (e.g. Heiken and Wohletz, 1985; Zimanowski et al., 2003; Proussevitch et al, 2011). Such two-dimensional "shadow" image of ash grains is hereafter named APASH, for Apparent (2D-)Projected shape of ASH. These works use the APASH as a source material, while the development of image analysis softwares in the eighties–nineties has conducted to the automatic determination of basic quantitative shape descriptors, such as length (L), width (W), perimeter (P) and area (A). These metrics were also combined to derive dimensionless parameters such as circularity (C_c), compactness (C_p) and elongation (Table 3). Additional advances in shape characterization of small volcanic clasts include cluster analysis of apparent 2D morphological features, fractal, multifractal and pseudofractal dimensions of particle outlines, luminance of ash grains, and also address specific statistical processing techniques (e.g. Dellino and La Volpe, 1996b; Dellino and Liotino, 2002; Maria and Carey, 2002; Scasso and Carey, 2005; Kueppers et al., 2006; Perugini et al., 2011; Proussevitch et al, 2011; Jordan et al., 2014; Miwa et al., 2015). Concomitantly, recent research has explored the 3D shape of fragmented volcanic rocks, using for example 3D images of a few grain through tomographic and shadow imaging techniques (Montenegro Rios et al., 2013; Bagheri et al., 2015) and similar techniques have been extended to other grain types (e.g. Erdogan et al., 2007). In addition, pseudo-3D information of ash morphology has been obtained with illumination functions of volcanic grains (e.g. Ersoy et al., 2010), involving typically less than a few tens of particles in the analyses.

All these works have indisputably brought substantial improvements in methodological and volcanological terms. Nevertheless, some limiting concerns have hampered generalizing these methods for extended applications and inter-laboratory comparisons. On one hand, most 3D imaging techniques are time-consuming and expensive, and are used solely on a small number of grains (Rausch et al., 2015;