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Timing and nature of volcanic particle clusters based on field and numerical investigations

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ABSTRACT

Aggregation processes are known to play an important role in volcanic particle dispersal and sedimentation. They are also a primary source of uncertainty in ash dispersal forecasting since fundamental questions, such as the timing and deposition dynamics of volcanic aggregates, still remain unanswered. Here, we applied a state-of-the-art combination of field and numerical strategies to characterize volcanic aggregates. We introduce a new category of aggregates observed with high-speed-high-resolution videos, namely cored clusters. Cored clusters are mostly sub-spherical fragile aggregates that have never been observed in the deposits nor on adhesive tape as they typically break at impact with the ground. They consist of a core particle (200–500μm) fully covered by a thick shell of particles < 90μm. The low preservation potential of cored clusters in ash deposits explains the poor documentation in the literature and the low consideration attributed so far. Cored clusters can also better explain the deposition of fine ash in proximal and medial regions and the polymodality observed in many ash deposits. In addition, numerical inversions show how cored clusters can rapidly form within 175s from eruption onset. Finally, our observations represent the first field-based evidence of the so-called rafting effect, in which the sedimentation of coarse ash in cored clusters is delayed due to aggregation.

1. Introduction

Dispersal and deposition of ash during volcanic explosive eruptions strongly affect the surrounding environment and distal atmosphere, with disruptive consequences on local communities and both land and aviation transport (Blong, 1984; Guffanti et al., 2010). Aggregation processes are well known to affect sedimentation of fine ash (< 63 μm) by considerably reducing its residence time in the atmosphere (e.g. Brown et al., 2012; Durant, 2015; Lane et al., 1993; Rose and Durant, 2011). If particle aggregation is not considered, volcanic ash transport and dispersal models fail to accurately describe both particle deposition in proximal areas and atmospheric ash concentration in the far field, with important implications for both hazard assessment and real-time ash forecasting (e.g. Brown et al., 2012; Folch et al., 2010; Rose and Durant, 2011).

Volcanic particles mainly collide and cluster because of complex interactions of surface liquid layers, electrostatic forces, turbulence and/or differences in settling velocities. Depending on the water content, particle aggregation results in the formation of *particle clusters* and/or *accretionary pellets* (e.g. Brown et al., 2012; Sparks et al., 1997). Based on the classification introduced by Brown et al. (2012), the category of particle clusters (also known as *dry aggregates* in previous literature) includes both *ash clusters*, noted as PC1, and *coated particles*, noted as PC2 (see Fig. 1). Ash clusters are defined as fragile irregular shaped aggregates composed of particles *typically* < 1 μm–40 μm, whereas coated particles are defined as fragile aggregates comprised of a crystal, crystal fragment, pumice or lithic clast *partially* covered with fine ash particles. The category of accretionary pellets comprises poorly structured pellets, noted as AP1, pellets with concentric structures (also known as *accretionary lapilli*), noted as AP2, and *liquid pellets* (also known as mud rain), noted as AP3 (Brown et al., 2012).

During the last two decades, several experimental, numerical and field investigations have been carried out to describe aggregation processes in terms of grain-size distribution, terminal velocity,

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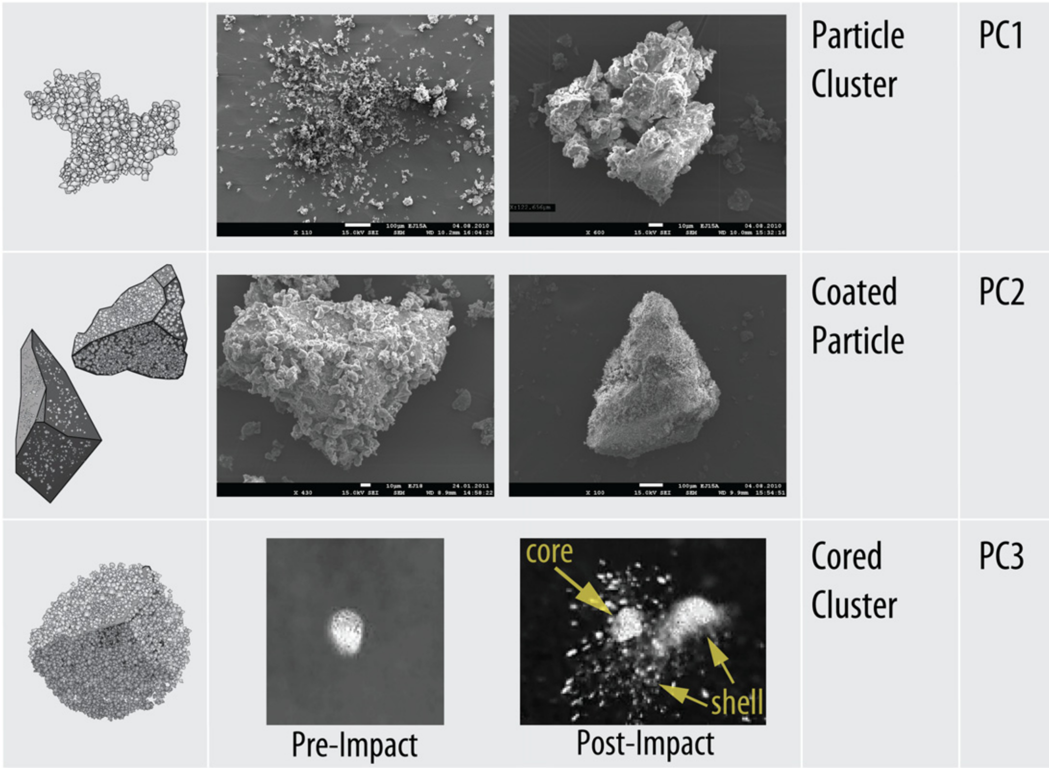

Fig. 1. Schematics and images of various types of particle clusters' (PC) family including ash clusters (PC1), coated particles (PC2) (following the notation of Brown et al., 2012) and the newly introduced category of cored clusters (PC3). Images of PC1 and PC2 are from Eyjafjallaj okull 2010 eruption (Bonadonna et al., 2011), while images of PC3 are obtained from a HS-HR video of a Sakurajima 2013 explosion (this work); also see Fig. 5A and supplementary videos for more details on PC3.

structure, density and porosity (Bonadonna et al., 2011; Gilbert and Lane, 1994; James et al., 2002; Lane et al., 1993; Mueller et al., 2016; Schumacher, 1994; Schumacher and Schmincke, 1995; Taddeucci et al., 2011; Telling et al., 2013; Van Eaton et al., 2015; Van Eaton and Wilson, 2013). However, due to the low preservation potential of particle clusters and most accretionary pellets in deposits, most studies focused on the characterization of the more resistant well-structured pellets (i.e. accretionary lapilli; Gilbert and Lane, 1994; Van Eaton et al., 2015; Van Eaton and Wilson, 2013). In addition, aggregate classifications available in literature are mostly based on both field observations of deposits and scanning electron microscope (SEM) analysis of aggregates sedimented on adhesive tape (e.g. Brown et al., 2012; Sparks et al., 1997; Van Eaton and Wilson, 2013).

Here we introduce new high speed-high resolution (HS-HR) observations that reveal additional complexities of particle clusters. In particular, we focus on the relation between ash clusters and coated particles (in the notation of Brown et al., 2012) and we introduce an additional category of aggregates observed with HS-HR videos, namely *cored clusters* (which we define here as PC3 adding on the original terminology of Brown et al., 2012, that firstly introduced PC1 and PC2). Cored clusters are mostly sub-spherical fragile aggregates that have never been observed in the deposits nor on adhesive tape as they typically break at impact with the ground (Fig. 1). They consist of a *core particle* (coarse ash to fine lapilli size) fully covered by a thick *shell* of particles < 90 μm.

It is important to note that cored clusters here are different from *poorly-structured pellets, AP1* (Brown et al., 2012), that include *core-type accretionary lapilli* (Schumacher and Schmincke, 1991), *Type II accretionary lapilli* (Reimer, 1983) and *ash pellets* (Brown et al., 2012; Thordarson, 2004). In fact, the more fragile cored clusters described here break at impact with the ground; as a result, they more appropriately belong to the particle cluster category. They also differ from the *well-structured accretionary pellets, AP2* (Brown et al., 2012), that include *rim-type accretionary lapilli* (Schumacher and Schmincke, 1991), *Type I accretionary lapilli* (Reimer, 1983), *armored lapilli* and *cored lapilli* (with lithic or pumice cores) *accretionary lapilli* and *coated pellets* (Brown et al., 2012), as the cored clusters described here do not present any internal structure.

Field studies of particle clusters (both ash clusters and coated particles) include the investigations of the 1980 eruption of Mount St. Helens, USA (Sorem, 1982), the 1990–1994 eruptions of Sakurajima volcano, Japan (Gilbert et al., 1991; Sparks et al., 1997), the 1997 eruption phase of Soufriére Hills volcano, Montserrat (Bonadonna et al., 2002b) and the 2010 eruption of Eyjafjallajökull volcano, Iceland (Bonadonna et al., 2011; Taddeucci et al., 2011). Sorem (1982) observed ash clusters with diameters between 250 μm to 500 μm about 390km from the vent that were composed of ash 40 μm. He also reported that large ash particles (40 μm to 60 μm) deposited as aggregates far beyond the distance at which they would have settled if traveling independently. This phenomenon is known as *rafting*, which results in the delayed sedimentation of large particles due to coating of fine ash of low bulk density and falling at a lower settling velocity.

Gilbert et al. (1991) and Sparks et al. (1997) reported ash clusters at Sakurajima volcano with diameters < 3 mm, which consisted of particles < 200 μm, whereas coated particles had diameters > 200μm and were covered with particles < 20 μm. Bonadonna et al. (2002a) observed both types of aggregates (i.e. ash cluster and coated particle) resulting from either dome collapses or Vulcanian explosions at Soufriére Hills volcano. Finally, Bonadonna et al. (2011)