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Silicate glass micro and nanospherules generated in explosive eruptions of ultrabasic magmas: Implications for the origin of pelletal lapilli

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ABSTRACT

The genesis of spherical ash to lapilli-sized clasts with a central phenocryst or lithic fragment, mantled by a rim of fine-grained juvenile material that includes abundant concentrically arranged prismatic crystals, is interpreted as either: (i) the result of the spinning of a magma bleb with a crystalline kernel in a fluidized system, or (ii) the accretion of small melt droplets to a previously crystallized nucleus in a gas jet. We demonstrate that the rims of pelletal lapilli within tephras of the Cabezo Segura volcano (Calatrava, Spain) are clastic and were formed by the progressive welding of juvenile crystals and silicate glass droplets, and, to a lesser extent, filaments (both melt in origin) around a large crystalline nucleus. Our results support the accretion hypothesis and offer explicit and new images of the melt droplets that were so far considered hypothetical particles. These results indicate also that nanometre-scale juvenile pyroclasts (melt droplets and crystals) can be generated in explosive eruptions of ultrabasic magmas. Those pyroclasts can be subsequently welded together inside a dense gas jet generating pelletal lapilli and ash.

1. Introduction

Pelletal lapilli are discrete, spherical-to-elliptical clasts that consist of fine-grained primary igneous material and typically range in size from <1 to 60 mm (Mitchell, 1997). Commonly, those lapilli contain at their centres a single, relatively large euhedral crystal or crystal fragment. These cores or kernels typically consist of olivine and, more rarely, phlogopite, clinopyroxene (Stoppa et al., 2000; Stoppa and Schiazza, 2013), titaniferous magnetite (Campeny et al., 2014) or also country rock microxenoliths (Rosatelli et al., 2003; Campeny et al., 2014). Mantles, or rims, are composed of fine-grained microphenocryst material in which prismatic minerals are commonly flow-aligned (e.g., Mitchell, 1997). Pelletal lapilli have been identified globally in a wide range of volcanic rocks including kimberlites (Mitchell, 1997; Brown et al., 2012), carbonatites (Stoppa, 1996; Lloyd and Stoppa, 2003; Campeny et al., 2014), kamafugites (Junqueira-Brod et al., 1999, 2004, 2005), melilitites (Stoppa, 1996; Mitchell, 1997), orangeites (Mitchell, 1997) and nephelinites (Carracedo Sánchez et al., 2009; Carracedo et al., 2009, 2010; Stoppa et al., 2011), and have been referred to, for instance, as tuffisitic lapilli (Stoppa, 1996), spherical lapilli (Keller, 1981), spinning droplets (Junqueira-Brod et al., 1999, 2004, 2005; Carracedo Sánchez et al., 2009; Carracedo et al., 2009, 2010), concentrically shelled lapilli (Stoppa and Principe, 1998) and cored lapilli (Lefebvre et al., 2005; Stoppa et al., 2011).

The genesis of pelletal lapilli is under discussion. Some authors (e.g., Clement, 1973; Dawson, 1980; Junqueira-Brod et al., 1999, 2004, 2005) suggest that their spherical to disc-shaped form is due to the spinning of magma clots with a crystalline kernel inside a fluidized system, which implies: (i) that the magma clots spin in the conduit orienting the crystals (microphenocrysts and microlites) around the crystal core; (ii) while spinning, the magma clots lose part of the liquid fraction concentrating crystals, and (iii) the rotation, combined with the increase in crystals/groundmass ratio, result in the final, spherical, concentric particle. Other authors (e.g., Lorenz, 1979; Lloyd and Stoppa, 2003; Gernon et al., 2012) suggest that the pelletal lapilli result from the adherence of small melt droplets (lava spray) and crystals to a previously crystallized central fragment due to surface tension, followed by rotation of the pelletal lapilli during transport. Theoretically, this debate should be easily solved by demonstrating whether the rim of pelletal lapilli is coherent, i.e., formed from a magma clot, or clastic, i.e., formed by accretion of particles (magma droplets and clasts) to a central crystal/fragment. However, the question remains unsolved because the accurate nature of the rim groundmass is normally unknown due to its alteration.

In some cases, it has been observed that the rim is a dense mass of microphenocrysts with a concentric flow texture set in devitrified glassy matrix, almost entirely transformed into a mixture of clay minerals (Junqueira-Brod et al., 2005). But, the original character (coherent or originated by agglutination/coalescence of magma droplets) of this devitrified matrix remains unknown. Recent studies on the origin of pelletal lapilli (e.g., Gernon et al., 2012) suggest that melt droplets

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conveyed by explosive magma fragmentation may be deposited onto crystalline hot particles and create a thin film over which very fine ash is agglutinated to form pelletal lapilli, in a similar process to industrial fluidized spray granulation. Nevertheless, no evidence has been provided hitherto of such droplets which, hypothetically, form the crystals mortar in the pelletal lapilli rim.

Here we present the results of a study carried out on pelletal lapilli identified inside the ash and lapilli tephras of the Cabezo Segura volcano. This edifice is located in the Calatrava Volcanic Field Region of south central Spain (López Ruiz et al., 2002; Ancochea, 2004). A careful study by optical and Scanning Electron microscopy (SEM), and analysis by energy dispersive X-ray spectrometry methods (EDX) has allowed us to discover silicate glass micro and nanospheres formed by cooling of melt droplets, thus confirming the fragmental nature of the rim and, thereby, validating the accretion hypothesis. We argue that the pelletal lapilli might in effect have been formed by a similar process to the fluidized spray granulation, as proposed by Gernon et al. (2012), but within the bounds of a gas jet from a fire fountain.

1.1. Geological setting

Alkaline anorogenic intra-plate magmatism was widespread in central and western Europe from early Tertiary to recent times (e.g., Wilson and Downes, 1991). In the Iberian Peninsula, this magmatism occurs mainly in the Volcanic Region of Girona (e.g., Martí et al., 2011), southeastern Pyrenees and in the Calatrava Volcanic Field of south central Spain (e.g., Cebriá and López Ruiz, 1995; Ancochea, 2004) (Fig. 1a).

The Calatrava Volcanic Field is located in the province of Ciudad Real and comprises more than 200 volcanoes dispersed across ca. 5500 km^2 (Fig. 1b). Strombolian and phreatomagmatic activity produced small-volume mafic volcanoes where cinder cones with associated lava flows and maars are abundant (Ancochea, 2004). Nonetheless, some fountain-fed deposits of this region, as spatter and lava-like bodies, are considered to have been generated during Hawaiian episodes (e.g., Carracedo Sánchez et al., 2012).

The volcanoes are situated over Variscan terrains irregularly covered by Cenozoic sediments (Ancochea, 2004). The Paleozoic basement includes Ordovician to Silurian quartzites, limestones and slates, all of them variably deformed during the Variscan and Alpine orogenies. This basement is unconformably overlain by fluvial and lacustrine sediments deposited in small basins, formed since the late Miocene in relation with an extensional tectonic regime (López Ruiz et al., 2002).

The volcanic rocks are olivine melilitites, nephelinites, alkaline basalts, basanites and olivine leucitites (Ancochea, 2004). Two main phases of volcanic activity involved a first ultrapotassic stage, starting in the late Miocene (8.7–6.4 Ma) with the emission of leucitites, followed 1.7 My later by relatively voluminous eruptions of sodic alkaline products (4.7 Ma; Ancochea, 1982).

This alkaline volcanism in mainland Iberia has been related to either a complex transtensional megafault to rift system that extends from North Africa to Scandinavia across the Spanish Mediterranean coast, France and Germany (Trans-Moroccan–Mediterranean–European fault system), or to a volcanic clustering related to asthenospheric mantle upwelling (hot-spot or diapir instabilities) in a pre-rifting stage (cf. Ancochea, 1982; Cebriá, 1992; López Ruiz et al., 2002 and references therein).

The Cabezo Segura volcano is a complex polygenetic volcanic cone located ca. 6 km to the SW of Ciudad Real and 1.5 km to the E of the Guadiana and Jabalón rivers junction (Fig. 1b, c). The volcano is the result mainly of Strombolian and Hawaiian eruptions with minor hydrovolcanic episodes, and is formed essentially by scoriaceous lapilli, spatter, lava-like bodies and composite spheroidal bombs and lapilli (Carracedo et al., 2009, 2010; Carracedo Sánchez et al., 2012). The effusive activity is represented by several ≤20 m thick and ≤2 km in length lava flows of basalt, basanite and melilite (Portero García et al., 1985). The lavas have been dated at 3.7 Ma (K–Ar; Ancochea, 2004). The only feeder dyke present in this volcano is made of ultrabasic rocks

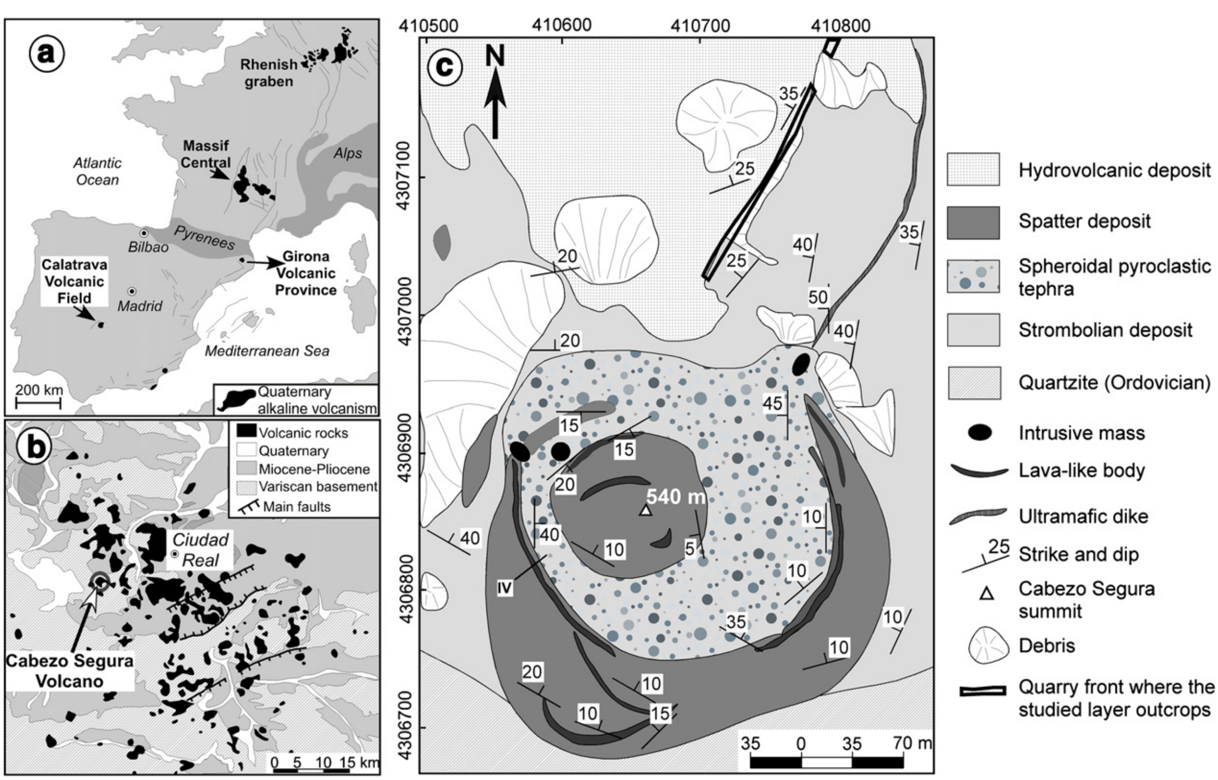

Fig. 1. a Early Tertiary and Quaternary alkaline anorogenic intra-plate magmatic provinces of central and western Europe (modified from Martí et al., 2011). b Simplified geological map of the Calatrava volcanic province (modified from Cebriá and López Ruiz, 1995) showing the location of the Cabezo Segura volcano. c Geological sketch map of the Cabezo Segura volcano outlining the position of the studied tephra layer.