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Evolution of the mafic Villa Senni caldera-forming eruption at Colli Albani volcano, Italy, indicated by textural analysis of juvenile fragments

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ABSTRACT

The Villa Senni Formation (355 ka) represents the youngest mafic caldera-forming eruption of the Colli Albani Volcano (Central Italy), and one of the best exposed large mafic ignimbrite successions on Earth. The unusual Si-undersaturated and high-K composition of the magma, and corresponding low magma viscosity, raise important questions about the conditions of magma ascent, eruption, and fragmentation that led to such a large explosive eruption. We examined the juvenile clast textures – that is, the abundance, shape, size and number density of both vesicles and leucite microlites – to reconstruct the fragmentation conditions and to trace major changes in the ascent rate and vesiculation history of the magma associated with caldera collapse. The juvenile textures record two major changes in the eruption dynamics through the stratigraphy. First, the sudden depressurization of the magma chamber and the onset of the first ignimbrite-forming phase are marked by a dramatic increase in the magma ascent velocity inferred by a decrease in vesicle and leucite microlite sizes and increase in their number densities. Second, the progressive restoration of pressure within the magma reservoir as a consequence of caldera collapse is recorded by an inversion of vesicle and leucite microlite textures, which suggest a strong decrease in magma ascent rate. Complex vent conditions in this later phase of the caldera collapse are recorded by the diversity of textural features, variation in magma chemistry and the abrupt changes in the stratigraphic record (including the presence of co-ignimbrite breccias, spatter clasts and lithics).

1. Introduction

Caldera-forming eruptions are some of the most dangerous volcanic events on Earth, not only because they involve large volumes of erupted material, but also because of their highly explosive character (Cas and Wright, 1987). In recent decades, advances in understanding caldera-forming eruptions have come from detailed field studies (e.g. Bacon, 1983; Fisher et al., 1993; Allen and Cas, 1998; Bear et al., 2009a), laboratory analyses (e.g. Gurioli et al., 2005; Adams et al., 2006), and analogue and numerical modelling (e.g. Martí et al., 2000; Cole et al., 2005; Geyer et al., 2006; Acocella, 2007; Martí et al., 2009). However, most of this work has focused on the deposits (and mechanisms) of felsic magmas (Jellinek and DePaolo, 2003; Geyer and Martí, 2005 and references therein), where high magma viscosity and delayed bubble nucleation can combine to generate energetic eruptions. Recently it has been shown, however, that basaltic magmas can also generate highly explosive eruptions, as exemplified by eruptions of Etna 122 BC (Coltelli et al., 1998; Sable et al., 2006a), Fontana Lapilli (Costantini et al., 2009, 2010), Masaya Triple Layer (Pérez and Freundt, 2006; Perez et al., 2009), and Tarawera 1886 (Sable et al., 2006a,b, 2009). Basaltic explosive eruptions can also trigger caldera formation, as illustrated by the Il Piano Caldera on Etna (Coltelli et al., 1998) and the Masaya caldera in Nicaragua (Pérez and Freundt, 2006), although the mechanism by which caldera formation occurs is poorly understood. What is most intriguing about caldera-forming, explosive eruptions of mafic magma, or highly undersaturated potassic magma such as at Colli Albani (Giordano et al., 2006; Boari et al., 2009; Giordano and the CARG Team, 2010), is that their occurrence implies an effective and prolonged coupling between the exsolving volatile phase and magma during vesiculation; in low viscosity magma, this requires sufficiently rapid magma rise to prevent extensive gas–liquid segregation.

It is well known that magma behaviour during vesiculation and fragmentation is influenced by magma composition and viscosity (Gardner et al., 1996; Dingwell, 1998; Papale et al., 1998; Papale and Polacci, 1999), volatile content (Papale et al., 1998; Giordano et al.,

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2005) and magma ascent rate (Jaupart, 1996; Parfitt, 2004; Sable et al., 2006a, 2009). Textural studies of mafic pyroclasts attest to the changes in bubble and crystal content, and therefore in magma rheology, caused by magma ascent and degassing (Polacci et al., 2003; Sable et al., 2006a, 2009; Wright et al., 2009; Costantini et al., 2010). Depending on initial magma crystallinity, the degree of supersaturation and ascent rates, bubble nucleation can occur by homogeneous or heterogeneous mechanisms, which control the history of bubble growth during ascent (Cashman, 2004 and references therein). The interconnectivity and the complexity of the developing bubble network influence the permeability of magma (Rust and Cashman, 2004, 2011) and therefore the extent to which exsolved volatiles can maintain coupling with the magma during ascent, as well as the degree of gas overpressure within bubbles; together these combine to control both the explosivity and fragmentation efficiency of the resulting eruption (Klug and Cashman, 1996; Saar and Manga, 1999; Larsen et al., 2004; Takeuchi et al., 2005; Nakamura et al., 2008; Wright et al., 2009). Rates of bubble formation, deformation and coalescence depend on the rheology of the melt (+/− crystals), which may change by orders of magnitude with rapid syn-eruptive growth of microlites (e.g. Mètrich et al., 2001; Hammer and Rutherford, 2002), degassing (Hess and Dingwell, 1996), and variations in shear rate (e.g. Rust et al., 2003; Rosi et al., 2004).

Textural data are an excellent proxy for eruption dynamics, and, if constrained by a well defined 3D stratigraphic architecture of the associated deposit, can provide important constraints on the spatial and temporal evolution of eruptions. In particular, textural studies have the potential to provide important insights into conditions of caldera collapse, where variations in magma chamber pressure (e.g. Martí et al., 2000, 2009) and conduit configuration (e.g. Druitt and Bacon, 1986; Rosi et al., 1996; Bear et al., 2009b) may be recorded in the bubble and crystal populations. However, to date, detailed studies of ignimbrites are available only for silicic eruptive deposits such as those of the Campanian Ignimbrite (Polacci et al., 2003), Vesuvius 79 A.D. (Gurioli et al., 2005), Mt. Mazama 7700 BP (Klug et al., 2002) and Taupo 1.8 ka (Houghton et al., 2010). Additionally, of these studies, only that of Gurioli et al. (2005) examines the relationship between the dynamics of caldera collapse and subsequent phases of the eruption. Furthermore, such studies have not yet been performed for large mafic ignimbrite eruptions, such as the Villa Senni Eruption, Colli Albani.

We present new data on textures of scoria and spatter clasts from the ≈355 ka, tephri-phonolitic to tephritic, caldera-forming Villa Senni Formation (VSN) at Colli Albani volcano. We classify the juvenile clasts types based on their vesicularity and crystallinity, as well as measurements of their permeability characteristics, and place them within the broader context of the reconstructed stratigraphy and physical volcanology of the eruption sequence. Data analysis framed by the stratigraphic architecture of the VSN deposit allows us to reconstruct changes in magma vesiculation and fragmentation during the eruption from the onset, to the vent widening phase, to ring fracture opening and caldera collapse, to the final post-climactic phase of the eruption. Our results allow us to address the following questions:

(1) which factors control the explosive behaviour of undersaturated, low vesicularity magmas?
(2) what is the role of leucite microlites in the fragmentation of the Colli Albani magma?
(3) how does a poorly vesicular magma fragment and sustain a large-volume caldera-forming ignimbrite eruption?

By combining field and textural data, this study not only improves our understanding of the Villa Senni eruption, but also provides new insights into caldera-forming eruptions of mafic volcanoes that may be equally relevant to felsic systems. In particular, we document varying eruption conditions that can be explained by first depressurisation and then repressurisation of the magma storage region as caldera collapse progresses.

2. Geologic background

Colli Albani is a Quaternary volcano near Rome. It is part of the Roman Magmatic Province and has been active for 600 ka (Chiarabba et al., 2010; Giordano and the CARG Team, 2010; Mattei et al., 2010) (Fig. 1). The compositions of the Colli Albani magmas range from melilite-bearing leucitites to tephrites to tephri-phonolites (Boari et al., 2009; Conticelli et al., 2010). In spite of the undersaturated and ultrapotassic character of the magma, however, the early period of volcanic activity (Vulcano Laziale period; 600–355 ka) was characterised by highly explosive eruptions that produced large, low aspect ratio ignimbrites (10–100 km^3 deposit volumes) and formed an 8×8 km^2 caldera (Giordano and Dobran, 1994; Palladino et al., 2001; De Rita et al., 2002; Giordano et al., 2006; Giordano and the CARG Team, 2010; Freda et al., 2011).

The last major caldera-forming eruption of the Vulcano Laziale period occurred at ~355 ka (cf. Soligo and Tuccimei, 2010 and references therein) and emplaced the Villa Senni Formation (VSN), the object of the present study. Previous work on this unit includes preliminary petrological and stratigraphic reconstructions (Freda et al., 1997; Watkins et al., 2002; Giordano and the CARG Team, 2010) that constrain the bulk volume to ~50 km^3 (made up of 30 km^3 of outflow sheets and 20 km^3 of intracaldera deposits), equivalent to 30 km^3 Dense Rock Equivalent (DRE) magma and indicating caldera collapse of 450 m (Giordano and the CARG Team, 2010).

Post-caldera activity has been characterised by the growth of an intracaldera stratovolcano as well as peri-caldera coalescent scoria cones and lava flows (Tuscolano–Artemisio and Faete period; 355–180 ka). The most recent activity at Colli Albani has been largely phreatomagmatic (Via dei Laghi period); the volcano is presently quiescent except for persistent emissions of CO_2 (Funiciello et al., 2003; De Benedetti et al., 2008).

3. Summary of the Villa Senni Formation stratigraphy and composition

The Villa Senni Formation covers more than 1600 km^2 and is distributed symmetrically around the volcano (Fig. 1). The aspect ratio of the deposit (the ratio of the average thickness of the deposit to its horizontal extent) is 3×10^{-4}, making it a low aspect ratio ignimbrite (sensu Walker, 1983). The maximum distance of preserved deposits from caldera centre is ca. 30 km and ignimbrite deposits are found across topographic obstacles as high as 450 m, more than 20 km away from source (Giordano and the CARG Team, 2010). From base to top, the Villa Senni Formation is composed of (Fig. 2): (1) a basal scoria lapilli fallout and surge deposit, dispersed to the east and with a maximum thickness of 140 cm (VSN0); (2) the indurated Tufo Lionato ignimbrite (>10 km^3 of outflow deposit) (VSN1), generally 5–10 m thick and characterised by three superposed lithofacies that can be distinguished on the basis of componentry and colour as the yellow (VSN1y), red (VSN1r) and brown (VSN1b) facies (cf. Watkins et al., 2002); (3) a sequence of scoria- and spatter-rich, co-ignimbrite lithic breccias (VSN2bsc and VSN2bsp respectively) that outcrop in proximal locations and as far as 7 km away from caldera rim; the spatter-rich breccias outcrop only in the north and north-western proximal slopes of the volcano; (4) the unconsolidated Pozzolanelle ignimbrite (>20 km^3 of outflow deposit) (VSN2), generally 10–20 m thick and homogeneous; and (5) a rarely preserved sequence of scoria lapilli fallout deposits that lie directly on top of the Pozzolanelle (VSN3).

The Villa Senni Formation is compositionally zoned. The bulk composition of the juvenile clasts of the lower (VSN1) Tufo Lionato ignimbrite is tephri-phonolitic, whereas it is phono-tephritic to