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The origin of a zoned ignimbrite: Insights into the Campanian Ignimbrite magma chamber (Campi Flegrei, Italy)

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ABSTRACT

Caldera-forming eruptions, during which large volumes of magma are explosively evacuated into the atmosphere from shallow crustal reservoirs, are one of the most hazardous natural events on Earth. The Campanian Ignimbrite (CI; Campi Flegrei, Italy) represents a classical example of such events, producing a voluminous pyroclastic sequence of trachytic to phonolitic magma that covered several thousands of squared kilometers in the south-central Italy around 39 ka ago. The CI deposits are known for their remarkable geochemical gradients, attributed to eruption from a vertically zoned magma chamber. We investigate the relationships between such chemical zoning and the crystallinity variations observed within the CI pyroclastic sequence by combining bulk-rock data with detailed analyses of crystals and matrix glass from well-characterized stratigraphic units. Using geothermometers and hygrometers specifically calibrated for alkaline magmas, we reconstruct the reservoir storage conditions, revealing the presence of gradients in temperature and magma water content. In particular, we observe a decrease in crystallinity and temperature and an increase in magma evolution and water content from the bottom to the top of the magma chamber. We interpret these features as the result of protracted fractional crystallization leading to the formation of a cumulate crystal mush at the base of the eruptible reservoir, from which highly evolved, crystal-poor, water-rich and relatively cold melts were separated. The extracted melts, forming a buoyant, easily eruptible cap at the top of the magma chamber, fed the initial phases of the eruption, until caldera collapse and eruption of the deeper more crystalline part of the system. This late-erupted, crystal-rich material represents remobilized portions of the cumulate crystal mush, partly melted following hotter recharge. Our interpretation is supported by: 1) the positive bulk-rock Eu anomalies and the high Ba and Sr contents observed in the crystal-rich units, implying feldspar accumulation; 2) the positive Eu anomalies in the matrix glass of the crystal-rich units, testifying to the presence of liquid derived from partial melting of low temperature mineral phases within the crystal mush (mostly feldspars); 3) the Ba and Sr-rich rims in the feldspars and positive Eu anomalies in clinopyroxene rims, suggesting late rim growth from a locally enriched melt following cumulate mush remelting and 4) the occurrence of An-rich plagioclase, relict from a more mafic recharge, which acted as a heat source. Our model reconciles many observations made over the years on zoned deposits of such high-magnitude explosive eruptions, and provides a framework to understand magma chamber processes leading up to cataclysmic events.

1. Introduction

Understanding the mechanisms that lead to the generation of large upper crustal reservoirs resulting in large explosive eruptions is one of the most challenging tasks for modern volcanology. Zoned ignimbrites, which record significant compositional and thermal gradients in such shallow magma reservoirs, represent an exceptional archive of information on magma storage conditions and evolutionary processes (Civetta et al., 1997; Hildreth, 1981; Lipman, 1971; Smith and Bailey, 1966; Wark et al., 2007). The origin of chemical and thermal zoning has been debated for years, with hypotheses ranging from magma mixing (e.g. Dorais et al., 1991; Hervig and Dunbar, 1992; Troll and Schmincke, 2002) to *in-*

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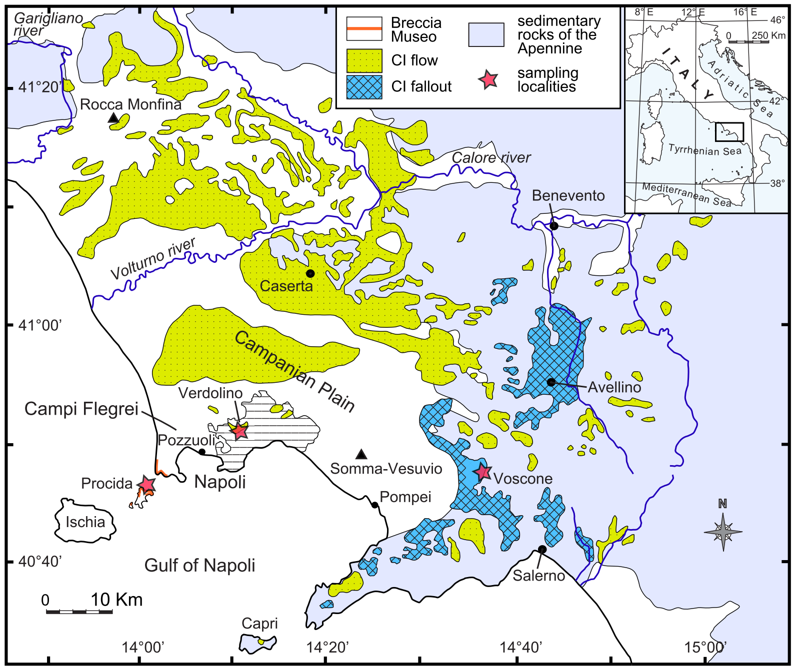

Fig. 1. Schematic map showing the distribution of the pyroclastic fallout and flow deposits referred to the Campanian Ignimbrite (CI) eruption (modified after Fulignati et al., 2004), the distribution of the Breccia Museo deposits (after Perrotta and Scarpati, 1994) and the sampling localities.

situ differentiation driven by crystal–liquid separation (e.g. Bacon and Druitt, 1988; de Silva, 1991; Hildreth, 2004). Although mixing of different magma batches remains popular as the cause of geochemical and isotopic heterogeneities in magma reservoirs (see also Bindeman and Valley, 2003; Sumner and Wolff, 2003), the importance of *in-situ* differentiation processes in generating and maintaining chemical and physical gradients, has been recently reiterated (Bachmann and Bergantz, 2008; Medlin et al., 2015; Sliwinski et al., 2015). In a fractional crystallization-dominated scenario, crystal–liquid separation occurs most efficiently at an intermediate crystallinity stage (∼50–70% crystals), when convection in the magma chamber has ceased (Bachmann and Bergantz, 2004). In this crystallinity window, conditions are suitable for hindered settling, microsettling and/or high permeability compaction to extract crystal-poor and highly evolved melts from the relatively high permeability crystal mush zones, generating a buoyant and easily eruptible cap in the upper part of the magma chamber (Dufek and Bachmann, 2010; Hildreth, 2004). Crystal cumulates can be remobilized by partial melting processes, which lower their crystallinity and increase their buoyancy, when heat and volatiles are transferred from mafic recharges (Huber et al., 2012; Parmigiani et al., 2014; Pistone et al., 2013). In this framework, it is the combination of *in-situ* differentiation and interaction with hotter recharges that is responsible for the generation of gradients in zoned ignimbrites (Deering et al., 2011; Pamukcu et al., 2013; Wolff et al., 2015).

In this paper, we focus on the Campanian Ignimbrite (CI), erupted at Campi Flegrei (southern Italy) during the largest volcanic event in the Mediterranean area over the past 200 ka. The CI is well-known for its remarkable bulk-rock geochemical variations that are observed from the bottom to the top of the pyroclastic sequence and have been attributed to eruption from a vertically zoned magma chamber (Arienzo et al., 2009; Civetta et al., 1997; Pappalardo et al., 2008; Signorelli et al., 1999). Despite the presence of a wide literature on the CI, the relationship between the chemical zoning and the processes that led to the growth of such a large magma reservoir in the upper crust remains controversial. In order to fill this gap, we combine new and literature data on bulk-rock major and trace elements from juvenile clasts with a detailed micro-analytical study of phenocrysts and coexisting glasses from well characterized stratigraphic units. Moreover, we use geothermometers, hygrometers and oxygen barometers specifically calibrated for alkaline magmas to estimate the pre-eruptive storage conditions and apply geochemical models to account for the behavior of key trace elements in the CI system.

2. Volcanological background

2.1. Campi Flegrei

The Campi Flegrei caldera is an active volcano located in the Campanian Plain (southern Italy; Fig. 1), a highly populated area affected by extensional tectonics since the Pliocene due to the opening of the back-arc Tyrrhenian basin behind the Apennine subduction zone (e.g. Scandone and Patacca, 1984). The time of onset of volcanism at Campi Flegrei is unknown; the oldest subaerial erupted products yield ages of about 60 ka and are related to volcanism extending beyond the limits of the present caldera (Pappalardo et al., 1999). However, geochronological investigations of drillcores from the Campanian Plain extend the age of the magmatic activity to over 200 ka (De Vivo et al., 2001). The present nested and resurgent caldera structure formed as a consequence of two cataclysmic explosive eruptions, the CI ($^{40}Ar/^{39}Ar$ age ∼39 ka, De Vivo et al., 2001; (U–Th)/He age ∼42 ka, Gebauer et al., 2014) and the Neapolitan Yellow Tuff (14.9 ka, Deino et al., 2004), during which ∼200 and ∼40 km^3 DRE (dense rock equivalent) of magma were respectively erupted (Civetta et al., 1997; Orsi et al., 1992). Within the last ∼15 ky, the Campi Flegrei caldera was the site of intense volcanic activity with more than 70 phreatomagmatic eruptions (Di Vito et al., 1999), the most recent of which built up the Monte Nuovo cone (A.D. 1538; Di Vito et al., 1987). Diffuse fumarolic and seismic activity and recurrent episodes of unrest have been also documented in the past 45 yrs (Orsi et al., 1999). The composition of magmas erupted within the Campi Flegrei caldera varies from shoshonite to phonolite, with trachyte and phonolite the most abundant (D'Antonio, 2011 and