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The eruption, pyroclastic flow behaviour, and caldera in-filling processes of the extremely large volume (>1290 km^3), intra- to extra-caldera, Permian Ora (Ignimbrite) Formation, Southern Alps, Italy

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ABSTRACT

The Permian Ora Formation (277–274 Ma) preserves the products of the Ora caldera 'super-eruption', Northern Italy. The stratigraphic architecture of the exceptionally well preserved intra-caldera succession provides evidence for caldera collapse at the onset of the eruption, a multiple discharge point, fissure eruption style, and progressive, incremental caldera in-filling by numerous pyroclastic flow pulses within the caldera. The ignimbrites of the Ora Formation are voluminous (>1290 km^3), crystal-rich (~25 to 55%), and ubiquitously welded. The Ora Formation has been divided into four members (a–d), which also define the principal eruption phases. The eruption proceeded in four main stages: (1) early caldera collapse and vent opening, producing locally distributed, basal co-ignimbrite lithic breccia (member a); (2) vent clearing, which produced the eutaxitic, lithic-rich ignimbrite and minor thin ground and ash-cloud surge deposits (member b); (3) waxing and steady eruption, which produced the dominant eutaxitic, coarse-crystal-rich ignimbrite, with local lithic-rich and fine-crystal-rich ignimbrite and minor surge deposits (member c); and (4) waning eruption, recorded by the eutaxitic, fine-crystal-rich ignimbrite, with local lithic-rich ignimbrite deposits (member d).

The incremental filling and late-stage outpouring of pyroclastic material from the caldera is recorded by vertical and lateral lithofacies deposit variation and some correlation between stratigraphic sections. These findings reveal a structure to the outwardly monotonous, >1300 m thick, intra-caldera fill and thinner (< 230 m) outflow successions. These data together with the gradational contacts between the main ignimbrite lithofacies, support the hypothesis that pyroclastic material was erupted from multiple source regions in various parts of the caldera, during quasi-steady, low eruption column collapse and pyroclastic flow forming events. Field study revealed the absence of a Plinian fallout deposit, suggesting a lack of a high, buoyant, Plinian precursor eruption phase. This caldera was initiated immediately by a low collapsing column phase, producing the main, thick ignimbrite succession. Simultaneously, catastrophic volcano-tectonic caldera collapse and decompression of the magma chamber occurred, facilitated by the regional extensional environment in the Permian and pre-existing crustal weaknesses. The Ora pyroclastic flow system is suggested as having been a hot and poorly expanded, high particle concentration, granular density current. The confined nature of the majority of the erupted products to the intra-caldera setting, reduced the formation of the full array of facies commonly expected in ignimbrites in extra-caldera settings.

1. Introduction

Extremely large volume (VEI 8: ≥1000 km^3) ignimbrites form during catastrophic 'supervolcano' caldera eruptions (Miller and Wark, 2008) and although no such eruption has been witnessed, they are potentially highly destructive. Therefore, there is an ongoing need to better understand caldera volcanoes (Lipman, 2000). Many questions remain about the processes occurring during large caldera eruptions, such as eruption initiation and style (e.g. Gottsmann et al., 2009; Gregg et al., 2012) and depositional processes within large pyroclastic flow systems (e.g. Fisher, 1966; Branney and Kokelaar, 2002; Cas et al., 2011; Doronzo, 2012), especially within calderas, which is a poorly understood aspect of pyroclastic density current volcanology.

Traditionally study of caldera-forming ignimbrites has been based mostly on deposits in the extra-caldera setting, leading to advanced knowledge of pyroclastic flow and caldera-forming processes, e.g. the

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Toba Tuff (e.g. Knight et al., 1986; Chesner, 2012); the Bishop Tuff (e.g. Wilson and Hildreth, 1997, 2003), the Bandelier Tuff (e.g. Smith and Bailey, 1966; Self et al., 1986), the Lava Creek Tuff, USA (e.g. Christiansen, 2001), the Fish Canyon Tuff, USA (e.g. Whitney and Stormer, 1985; Bachmann et al., 2002), the Lund Tuff, USA (e.g. Maughan et al., 2002); and large Andean calderas, South America (e.g. Sparks et al., 1985; de Silva et al., 2006; Folkes et al., 2011), to name but a few.

In contrast, there are far fewer studies on the characteristics of intra-caldera deposits and processes, e.g. calderas of the English Lake District (Branney, 1991; Beddoe-Stephens and Millward, 2000); Late Devonian to Permian calderas in Southern Australia (McPhie, 1986; Birch, 2003; Cas et al., 2003); the Chegem Tuff, Russia (Bogatikov et al., 1992; Lipman et al., 1993); Sesia caldera, Italy (Quick et al., 2009; Sbisà, 2012); Tertiary systems in the western United States such as the San Juan Volcanic Field, Colorado (Lipman, 1976, 1984, 2007), Timber Mountain Tuff, Nevada (Byers et al., 1976; Christiansen et al., 1977) and Caetano Tuff, Nevada (John et al., 2008). This is due primarily to the absence of exposure of the intra-caldera sequences, particularly the basal and floor sections, difficulty in access of large exposures, or difficulties arising from alteration and lithification of ancient deposits.

The Permian Ora Formation, in northern Italy, preserves an extremely large volume caldera-fill ignimbrite succession. This sequence has been incised and offers extensive cross-sectional exposure of the intra-caldera sequence, access to the caldera floor, as well as part of the outflow deposits. It is therefore, ideal to develop an understanding of the characteristics of intra-caldera fill ignimbrite sequences and their emplacement processes. The Ora Formation ignimbrite eruption is the youngest of five major ignimbrite eruptions from the Athesian Volcanic Group (Table 1), which represents the remains of a major nested caldera cluster. The aims of this paper are to develop a better understanding of (i) the eruption style(s) of large caldera volcanoes, (ii), the flow behaviours of large volume pyroclastic flows in the intra- and extra-caldera settings, and (iii) the way in which calderas are filled, using the ignimbrites of the Ora Formation as a case study.

2. Geologic setting

The Ora Formation dated between 277 ± 2 and 274.1 ± 1.6 Ma (Marocchi et al., 2008), is the youngest eruptive unit of the Athesian Volcanic Group (AVG), Southern Alps, northern Italy (Table 1). The AVG formed in a continental environment within the internal basins of the Variscan Orogenic Belt. These basins formed during large-scale extensional and strike-slip tectonic events associated with the collapse of the Variscan belt and later closure of the Paleo-Tethys Ocean (McCann et al., 2008; Cassinis et al., 2012). These events led to regionally widespread magmatism across Europe, including that represented by the AVG (Schaltegger and Brack, 2007; Quick et al., 2009; Cassinis et al., 2012). The Ora caldera complex sits within and upon older ignimbrite filled caldera structures and lava domes (Morelli et al., 2010). The area then became part of the African passive margin of the Tethys Ocean during the Mesozoic (Cassinis et al., 2012). Since then, the Southern Alps have remained remarkably stable (Ring and Richter, 1994), allowing erosion to produce the excellent exposures of the largely undeformed and unmetamorphosed Ora Formation and AVG system. The shielding of the region from intense Alpine deformation has been suggested to have resulted from the extensive volcanism during the Permian to Triassic periods, which developed a stable rigid crust in the region (Bonin et al., 1993; Ring and Richter, 1994; Castellarin and Cantelli, 2000; Schmid et al., 2004). The sub-horizontal dips in both the intra- and extra-caldera Ora ignimbrite (Fig. 1c), and lack of disruption of the fill sequence or evidence of post-emplacement faulting along the caldera margins, further indicate that the volcanic succession has neither been significantly deformed nor dismembered. The AVG and surrounding Permian plutons are constrained to the north by the Periadriatic lineament and to the south by the Valsugana line (Fig. 1b–c).

The AVG is a sequence of ignimbrites and subordinate lavas, domes, and sedimentary facies (Dietzel, 1960; Morelli et al., 2007; Schaltegger and Brack, 2007; McCann et al., 2008; Cassinis et al., 2012). The AVG stratigraphy has been recently defined through the Italian Geological Cartography or 'CARG' project 1:50.000 (AA.VV., 2007, 2010a,b, 2012). A major compositional change has been defined with a lower andesitic–rhyodacitic succession and upper rhyolitic succession (Morelli et al., 2007; Marocchi et al., 2008). The AVG unconformably overlies the South-Alpine Variscan metamorphic basement; it is in turn unconformably overlain by the upper Permian Val Gardena Formation, which represents the onset of the Alpine depositional cycle (Table 1; Dietzel, 1960; Morelli et al., 2007; Marocchi et al., 2008; McCann et al., 2008; Cassinis et al., 2012). The ignimbrites of the AVG have been previously described as thick, fairly homogeneous, welded, rhyodacitic–rhyolitic sequences (Morelli et al., 2007; Marocchi et al., 2008).

The Ora Formation has been mapped and described by Morelli et al. (2007), Marocchi et al. (2008), Morelli et al. (2010), where it was differentiated into two parts: the main thick, coarse grained formation and the smaller fine grained, Predonico member (Table 1). This current work builds on these important studies, with specific focus upon detailing the lithofacies and componentry of the Ora Formation, to gain further knowledge of the eruptive and caldera in-filling processes. The Predonico member is included within member d in this work (Table 1).

3. Field and laboratory methods

Stratigraphic logging, facies analysis, and detailed petrography were the essential methods used to characterise the deposits of the Ora Formation. These observations were used to interpret the large scale caldera eruption and pyroclastic flow processes. Stratigraphic logs were compiled at 16 locations. Due to the steep topography, some sections are composites, made up of numerous shorter sections, e.g. location 2 includes segments 2a–2e (Fig. 1c). The distribution of the field sites includes 8 in the Northern caldera depression, 4 in the Southern caldera depression and 5 in the northern outflow extra-caldera setting (Fig. 1c). These sections have been correlated here using lithofacies and textural characteristics.

Detailed petrography was undertaken on 195 thin sections to (i) characterise the componentry and texture of the ignimbrite facies, (ii) to define the intra-caldera stratigraphic architecture, (iii) to gain insight into the eruptive and pyroclastic flow depositional processes and finally, (iv) to gauge more accurately the degree of compactional welding and alteration within the deposit. Point counting of 128 thin sections was undertaken to determine the abundance of the main components of the ignimbrite and importantly, to help define vertical and lateral variations in componentry.

General lithification and syn- and post-emplacement welding of the ignimbrite deposit meant that sieving to gain quantitative grain size data was impossible. Free crystals in the matrix have therefore been used to distinguish different facies and sub-facies, using image analysis to obtain semi-quantitative data on the crystal size distributions of the free crystal population.

4. The Ora Formation: lithofacies

Extensive devitrification, welding, diagenesis and alteration have obliterated much of the primary ignimbrite textures (Willcock, 2013 p. 158–160). This has left no evidence of primary vesicle structures in mesoscopic juvenile clasts; however, some clasts still preserve flattened vesicle textures (Fig. 2a). Mesoscopic flattened fiamme typically define a eutaxitic texture at the outcrop scale, forming a moderate to well defined foliation (Fig. 2b–c). Mesoscopic glass shards are well preserved in some parts of the ignimbrite deposits, especially in the remarkably well preserved discontinuous basal vitrophyre lithofacies deposits (Fig. 2d). Where preserved, shards also show a eutaxitic texture, with plastic deformation features.