Journal of Volcanology and Geothermal Research 306 (2015) 17–40

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

A complex magma reservoir system for a large volume intra- to extra-caldera ignimbrite: Mineralogical and chemical architecture of the VEI8, Permian Ora ignimbrite (Italy)

M.A.W. Willcock [a,*], G.M. Bargossi [b], R.F. Weinberg [a], G. Gasparotto [b], R.A.F. Cas [a], G. Giordano [c], M. Marocchi [b,1]

[a] School of Earth, Atmosphere and Environment, Monash University, Clayton, VIC 3800, Australia
[b] Dipartimento di Scienze della Terra e Geologico-Ambientali, Università di Bologna, Piazza Porta San Donato, 1-40126 Bologna, Italy
[c] Dipartimento di Scienze Geologiche, Università di Rome Tre, Lago S. Leonardo Murialdo 1, 00146 Rome, Italy

ARTICLE INFO

Article history:
Received 13 April 2015
Accepted 4 September 2015
Available online 25 September 2015

Keywords:
Ora caldera
Northern Italy
Ignimbrite
Intra-caldera setting
Rhyolite
Caldera eruption dynamics

ABSTRACT

Intra-caldera settings record a wealth of information on caldera-forming processes, yet field study is rarely possible due to lack of access and exposure. The Permian Ora Formation, Italy, preserves >1000 m of vertical section through its intra-caldera succession. This provides an excellent opportunity to detail its mineralogical and geochemical architecture and gain understanding of the eruption evolution and insight into the pre-eruptive magma system. Detailed juvenile clast phenocryst and matrix crystal fragment point count and image analysis data, coupled with bulk-rock chemistry and single mineral compositional data, show that the Ora ignimbrite succession is rhyolitic (72.5–77.7% SiO_2), crystal-rich (~25–57%; average 43%) and has a constant main mineral population (volcanic quartz + sanidine + plagioclase + biotite). Although a seemingly homogeneous ignimbrite succession, important subtle but detectable lateral and vertical variations in modal mineralogy and bulk-rock major and trace elements are identified here.

The Ora Formation is comprised of multiple lithofacies, dominated by four densely welded ignimbrite lithofacies. They are crystal-rich, typically lithic-poor (<2%), and juvenile clast-bearing (average 20%). The ignimbrite lithofacies are distinguished by variation in crystal fragment size and abundance and total lithic content. The intra-caldera stratigraphic architecture shows both localised and some large-scale lithofacies correlation, however, it does not conform to a 'layer-cake' stratigraphy. The intra-caldera succession is divided into two depocentres: Southern and Northern, with proximal extra-caldera deposits preserved to the south and north of the system.

The Southern and Northern intra-caldera ignimbrite successions are discriminated by variations in total biotite crystal abundance. Detailed mineralogical and chemical data records decreases across the caldera system from south to north in biotite phenocrysts in the groundmass of juvenile clasts (average 12–2%), matrix biotite (average 7.5–2%) and plagioclase crystal fragments (average 18–6%), and total crystal fragment abundance in the matrix (average 47–37%); a biotite compositional change to iron-rich (0.57–0.78 Fe); and bulk-rock element decreases in Fe_2O_3, MgO, P_2O_5, Ce, Hf, V, La and Zr, and increases in SiO_2, Y and Nb, with TiO_2. Together, the changes enable subtle distinction of the Southern and Northern successions, indicating that the Northern deposits are more evolved. Furthermore, the data reveals discrimination within the Northern succession, with the northwestern extra-caldera fine-crystal-rich lithofacies, having a distinct texture, componentry and composition.

The componentry variation, mineralogical and chemical ranges identified here are consistent with an eruption from a heterogeneous magma system. Our results suggest that the Ora magma was likely stored in multiple chambers within a genetically related magma reservoir network. The mineralogical and chemical architecture together with stratigraphic relationships, enable interpretation of eruption sequence. Caldera eruption is proposed to have commenced in the south and progressed to the north, forming the two pene-contemporaneous caldera depressions. Moreover, this data illustrates heterogeneity and local zonation from base-to-top of the main intra-caldera and extra-caldera successions. These variations together with crystal fragment size variations between ignimbrite lithofacies support the hypothesis of a multi-vent eruption process, incremental caldera in-filling by subtly compositionally different pyroclastic flow pulses, and a lower intensity eruption style (Willcock et al., 2013, 2014).

* Corresponding author at: School of Earth, Atmosphere and Environment, P.O. Box 28E, Monash University, Clayton, Victoria 3800, Australia.
E-mail address: madelainewillcock@gmail.com (M.A.W. Willcock).
[1] Deceased.

http://dx.doi.org/10.1016/j.jvolgeores.2015.09.015

1. Introduction

Caldera volcano research is becoming ever more important as volcanic eruptions – even relatively small ones e.g. the 2010 Eyjafajallajokull eruption, Iceland (Gudmundsson et al., 2010) – are having greater impacts on society and the natural environment (Lipman, 2000; Bindeman, 2006). Understanding the very large active caldera systems, such as Yellowstone, USA (Girard and Stix, 2012), and Toba, Indonesia (Chesner, 2012), is paramount. Of the many unknown questions relating to calderas, the magma reservoir(s) (e.g. Smith and Bailey, 1966; Houghton et al., 1995; Bachmann et al., 2002; Jellínek and DePaolo, 2003; Hildreth, 2004; Bachmann and Bergantz, 2006, 2008; de Silva and Gosnold, 2007; Lipman, 2007; Huber et al., 2012; Cashman and Giordano, 2014), and eruption process (e.g. Druitt and Sparks, 1984; Lindsay et al., 2001; Maughan et al., 2002; Gravley et al., 2007; Hildreth and Wilson, 2007; Wolff et al., 2011; Cas et al., 2012; Ellis and Wolff, 2012; Gregg et al., 2012) are current foci of much research.

The intra-caldera succession is particularly useful as it can provide a more complete record of pre-eruptive magma genesis and caldera collapse, together with eruption and ignimbrite emplacement processes (Lipman, 1984). Access to the intra-caldera in active or recently active systems is generally not possible. When a deposit is sufficiently eroded, it may still be hard to access or too altered to study thoroughly. Therefore, well preserved, accessible intra-caldera deposits are scarce, e.g. Timber Mountain caldera, USA (Lipman, 1976, 1984; Christiansen et al., 1977), Stillwater Volcanic Complex, USA (John, 1995), Caetano Tuff, USA (John et al., 2008; MacDonald et al., 2012), Borrowdale Volcanic Group, United Kingdom (Beddoe-Stephens and Millward, 2000), or the Late Devonian to Permian calderas in Southern Australia (McPhie, 1986; Cas et al., 2003). The Permian Ora caldera in northern Italy, represents a little studied, large volume (>1000 km^3) rhyolitic caldera. Its excellent cross-sectional preservation of the intra-caldera fill presents a rare opportunity to detail the compositional architecture and processes of a major caldera-forming eruption. The Ora Formation records an extremely large caldera eruption, having a minimum erupted volume of >1290 km^3, an outcropping area of approximately 1500 km^2, and a host caldera with dimensions of ~42 × 40 km (Fig. 1c; Willcock et al., 2013). It records the last eruptive event of five major ignimbrite eruptions of the Athesian Volcanic Group, otherwise known as the Atesina Volcanic Complex (e.g. Barth et al., 1993; Bargossi et al., 2007; Marocchi et al., 2008), suggesting the incremental assembly of a batholithic scale magma system, comparable, for example, to the active Toba caldera system in Indonesia (Knight et al., 1986; Gardner et al., 2002; Chesner, 2012).

Initial examination of the Ora ignimbrite succession shows a broadly homogenous deposit, not uncommon for large ignimbrites which frequently have little apparent component or compositional variation. However, the apparent homogeneity can be deceptive and deposits vary from truly alike deposits known as ‘monotonous intermediates’ (Hildreth, 1981), e.g. the Fish Canyon Tuff (Bachmann and Bergantz, 2003; Bachmann et al., 2005; Charlier et al., 2007), Great Basin Province ignimbrites such as the Lund Tuff, Wah Wah Springs Tuff, Cottonwood Wash Tuff and Monotony Tuff (Ekren et al., 1971; Hildreth, 1981; Best et al., 1989; Maughan et al., 2002; Best et al., 2013), to those where trace elements and/or phenocryst populations, reveal subtle variation, e.g. the Bishop Tuff (Hildreth, 1979; Palmer et al., 1996; Wilson and Hildreth, 2003), ignimbrites of the Yellowstone caldera (Christiansen, 2001) and the Toba Tuff (Chesner, 1998). The aim of this paper is to present componentry, mineralogical and bulk-rock geochemical data to establish if the intra-caldera ignimbrite is indeed homogeneous, or if it shows compositional and mineralogical variations that can be used to understand the evolution of the Ora caldera eruption, the way the caldera was infilled, and the nature of the pre-eruptive magma system. Additionally, this study adds to the body of evidence on large caldera eruption processes.

2. Geological and geochemical background

The Ora Formation is the youngest (277 ± 2–274.1 ± 1.6 Ma; Marocchi et al., 2008) and best exposed eruptive unit of the Athesian Volcanic Group (285.4 ± 1.6–274.1 ± 1.6 Ma; Marocchi et al., 2008), located in the Southern Alps, northern Italy (Fig. 1). The entire Athesian Volcanic Group system formed in a continental setting, which was intermittently active over a 10 Myr period. There was a marked increase in eruption volume and frequency in the latter stages, which produced several large-volume rhyodacitic–rhyolitic ignimbrites (Table 1). The system also comprises subordinate andesitic–rhyolitic lavas and domes and minor epiclastic sedimentary material (Bargossi et al., 2004, 2007; Morelli et al., 2007; Schaltegger and Brack, 2007; Visoná et al., 2007; Marocchi et al., 2008). The Athesian Volcanic Group and the surrounding Permian intrusions are bounded by the Periadriatic lineament to the north and the Valsugana line to the south (Fig. 1b).

Magmatism occurring across Europe during the early Permian (e.g. Marti, 1991; Larsen et al., 2008) resulted from the collapse of the major Hercynian–Variscan orogenic belt and closure of the Palaeo-Tethys ocean (McCann, 2008; Cassinis et al., 2012). These events caused large-scale lithospheric thinning, basin formation, and thermal variability, resulting in many intrusive and extrusive magmatic events across Europe, including the Athesian Volcanic Group (Timmerman, 2004; Plant et al., 2005; Cassinis and Perotti, 2007; Marocchi et al., 2008; McCann et al., 2008; Timmerman, 2008). Importantly, the Athesian Volcanic Group succession has been influenced by the later Triassic marine transgression in the region, which leads to widespread hydrothermal fluid circulation, detected in the Athesian Volcanic Group rocks by shifts in geochemical and isotopic signatures (D'Amico and Del Moro, 1988; Barth et al., 1993; Rottura et al., 1998b). Previously published works on the Athesian Volcanic Group have focussed on the general stratigraphy and geochemical and isotopic characteristics as a whole (D'Amico et al., 1980; Bargossi et al., 1983, 1999, 2004, 2007; Berger and Satir, 1991; Barth et al., 1993; Bonin et al., 1993; Barth, 1994; Rottura et al., 1997, 1998a,b; Timmerman, 2004). These studies show a clear compositional change from a less evolved, lower Athesian Volcanic Group eruptive sequence (andesitic–rhyodacitic), to a more evolved upper Athesian Volcanic Group eruptive sequence (rhyolitic; Table 1), common of many long-lived silicic systems globally (Lipman et al., 1970; Lipman, 2007). Using samples primarily from the Ora ignimbrite, Barth et al. (1993) proposed that these magmas evolved in a compositionally zoned upper crustal magma chamber, inferred from moderate gradients of the major and trace elements and crossover of REE patterns (Barth et al., 1993).

2.1. The Ora Formation

Willcock et al. (2013) suggested that the Ora caldera was a volcano-tectonic system based on the following: the extensional basin environment during the Permian and the multiple prior caldera forming events of the Athesian Volcanic Group, together with the absence of the typical caldera eruption process (lack of a Plinian precursor eruption phase).

The succession is dominated by densely welded ignimbrite deposits (>1 km thickness in total; Willcock et al., 2013; Willcock and Cas, 2014), which are mostly confined within two intra-caldera depressions, Northern and Southern (capitals used here to distinguish the calderas, from general cardinal directions) separated by an intra-caldera ridge (Fig. 1c). Subordinate extra-caldera or outflow deposits are preserved up to 17 km from the margins of the complex correlated on the basis of field, petrographic and geochemical characteristics (<230 m thickness; Fig. 1c). This exceptionally well-exposed Permian ignimbrite succession is widely devitrified and shows some degree of alteration in places, yet remarkably still preserves local primary glassy domains (vitrophyre), primary welding textures (Willcock and Cas, 2014), and moreover, has been relatively unaffected by the later major Alpine orogenies (Bonin et al., 1993; Ring and Richter, 1994; Castellarin and