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Development, mobilisation and eruption of a large crystal-rich rhyolite: The Ongatiti ignimbrite, New Zealand

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ABSTRACT

The Ongatiti ignimbrite (>~500 km^3 DRE) was erupted at 1.21 ± 0.04 Ma from the Mangakino volcanic centre (Taupo Volcanic Zone, New Zealand). The ignimbrite is crystal rich (20–30%), of rhyodacite to low-silica rhyolite composition and lacks any consistent compositional zonation. Pumice whole-rock and glass compositions and crystal rim chemistries imply that the final erupted magma body was, to a first order, homogeneous, with the only variations reflecting crystal:glass proportions in analysed clasts. Crystals from pumices can be divided into two populations based on textural and chemical signatures: those that are inferred to have grown within the final erupted magma body (82% of plagioclase, 88% of orthopyroxene, 17% of amphibole), and those that originated in a chemically heterogeneous mush zone (18% of plagioclase, 12% of orthopyroxene, 83% of amphibole). Crystal-rich microcrystalline clasts, and clots within pumices, provide direct samples of parts of this heterogeneous source region. Amphibole model temperatures and pressures, coupled with in-situ trace element concentrations suggest that the mush region extended to ~15 km depth, near the base of the quartzofeldspathic crust and was rich in amphibole. Amphibole plus subordinate plagioclase and orthopyroxene, as well as antecrystic zircon were extracted from the crystal mush and ascended to a final storage region. Model temperatures and pressures from amphibole rims and Fe–Ti oxide model temperatures imply that the final erupted magma body was stored between 770 and 840 °C at 4–6 km depths. Homogenisation of the magma body occurred through convective stirring accompanying gradually rising temperatures induced by less-evolved magma(s) emplaced at deeper levels. Plagioclase records a steady core-to-rim increase in An content, implying that a gradual heating and/or increase in H_2O in the final erupted magma body occurred over some significant period prior to the eruption. No signals of a rapid defrosting or rejuvenation event that could be considered as an eruption trigger are recorded by the crystal phases. The Ongatiti ignimbrite has features both common to, and distinct from crystal rich 'monotonous intermediates' and crystal-poor compositionally zoned rhyolites. As such, the Ongatiti ignimbrite demonstrates that 'monotonous rhyolites' can also be developed on a large scale.

1. Introduction

Models to explain the magmatic processes involved in the generation, storage and eruption of large-scale silicic magma bodies have great diversity across the realm of volcanic rocks (e.g., Hildreth, 1981). Large felsic (dacite to rhyolite) volcanic ignimbrites, particularly examples from the central USA and Andes, are commonly placed into two categories (e.g., Bachmann and Bergantz, 2008; Huber et al., 2012): the crystal-rich monotonous intermediates of broadly dacitic composition (after Hildreth, 1981) and crystal-poor, compositionally zoned rhyolites. In overall models for the generation of rhyolite melts from crystal-rich mushes (Bachmann and Bergantz, 2004; Hildreth, 2004) these two categories are interpreted, respectively, to be remobilised crystal mushes and the fractionated melt (plus entrained and newly grown crystals) that has accumulated to form a stratified melt-dominant body. However, the melt-dominant bodies for several large crystal-poor New Zealand rhyolites, although compositionally variable, were not systematically zoned (Cooper, 2014; Cooper et al., 2012; Wilson et al., 2006). In the New Zealand ignimbrite record also, there are two super-sized eruption deposits that are crystal-rich and might ostensibly be interpreted as examples of remobilised mushes. The Whakamaru deposits (Brown et al., 1998a) are inferred to represent, in large part, a crystal-rich body that was reactivated over a short (centuries to millenia) period prior to eruption (Matthews et al., 2012a,b). The Ongatiti ignimbrite from Mangakino is also crystal-rich (20–30%), of rhyodacite to low-silica rhyolite composition, and shows compositional variability, but not consistent zonation (Briggs et al., 1993). Both these deposits, however, are quartz-bearing and have higher SiO_2 contents than the examples of monotonous intermediates widely cited in the literature, such as the Fish Canyon Tuff (Bachmann

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and Dungan, 2002; Bachmann et al., 2002), Cerro Galan ignimbrite (Folkes et al., 2011; Francis et al., 1989), Atana ignimbrite (Lindsay et al., 2001) and the Lund Tuff (Maughan et al., 2002).

The question then arises as to the origins of the magma bodies that fed eruptive units like the Whakamaru and Ongatiti ignimbrites. Do they simply represent remobilised crystal mushes activated by thermal rejuvenation, but of more evolved, quartz-bearing compositions? Alternatively, do they represent erupted melt-dominant bodies that had cooled and crystallised towards, but not to the point of critical crystallinity or rheological lock-up at >~50 vol.% crystals (Brophy, 1991; Huber et al., 2010a; Marsh, 1981; Petford, 2003; Vigneresse et al., 1996)? The rapid rates of generation and 'de-generation' by crystallisation of eruptible melt-dominant bodies implied by the Oruanui (and other young eruptions at Taupo: Allan et al., 2013; Sutton et al., 2000) suggest that evolved, hot, melt-bearing mush bodies may be commonly present in silicic volcanic systems. What would such a crystal-rich rhyolitic mush look like if 'defrosted' (Mahood, 1990) or 'reactivated' (Bachmann et al., 2002; Huber et al., 2010b)?

Important clues to understanding the genesis of the New Zealand 'monotonous rhyolites' lie in the compositions and textures of crystals that reflect the processes of heating and cooling, and the records of interstitial melt compositions. Although these deposits show limited bulk compositional variations, significant variability and a complex history of open-system magmatic processes may be recorded within the mineral assemblages (e.g., Charlier et al., 2008; Matthews et al., 2012a). The addition of heat is ubiquitous in any remobilisation process, commonly inferred to be the result of underplating by less evolved to wholly mafic compositions (Bachmann and Bergantz, 2003; Bachmann et al., 2002; Couch et al., 2001; Hildreth and Wilson, 2007; Murphy et al., 2000; Pallister et al., 1992). In addition, however, that heat may be introduced with and/or by inputs of volatiles (Sisson and Bacon, 1999; the 'gas sparging' or mafic 'wind' of Bachmann and Bergantz, 2006) and/or melts of contrasting (generally less-evolved) composition. Such inputs will be reflected in changes of composition in the interstitial melts/glasses and the crystals that dissolve in, or crystallise from, those melts.

In this paper we present data from the Ongatiti ignimbrite (>500 km^3 DRE) from Mangakino volcanic centre in the Taupo Volcanic Zone (TVZ), New Zealand, to explore the processes that gave rise to this large-volume crystal-rich deposit. We evaluate the homogeneity of the Ongatiti ignimbrite through whole-rock geochemistry of juvenile clasts (pumices), and explore the development of magma system thorough the textural history and in-situ analysis of the major mineral phases. The origins of each mineral phase and the involvement of a lesser-evolved source are investigated though the study of crystals and glass in microcrystalline clots, which are commonly found within pumices and as discrete clasts. The histories of the major crystal phases are evaluated also in the light of a protracted crystallisation record in Ongatiti U–Pb zircon age spectra (Cooper et al., under review).

2. Geological background

The Taupo Volcanic Zone (TVZ) is a NNE-trending, 300 km long and up to 60 km wide region of volcanism and associated extension active since ca. 2 Ma. It forms the continental continuation of the Tonga–Kermadec arc, associated with the westward subduction of the Pacific plate beneath the Indo-Australian plate (Cole, 1990; Cole and Lewis, 1981; Gamble et al., 1996; Wilson et al., 1995). The Mangakino volcanic centre is a composite caldera structure located on and in part defining the northwestern margin of the TVZ (Fig. 1). Activity at Mangakino can be subdivided into two intense periods of large caldera-forming eruptions from 1.60 to 1.53 Ma, and 1.21 to 0.95 Ma (Houghton et al., 1995).

The Ongatiti eruption occurred at 1.21 ± 0.04 Ma (Houghton et al., 1995) producing a voluminous (>500 km^3 DRE), widespread, crystal-rich, rhyodacitic to rhyolitic ignimbrite. The ignimbrite is widely distributed to the north (as far as Auckland: Alloway et al., 2004) and west (as far as the Tasman Sea coast: Pain, 1975), and is found to the southeast at depth beneath the Waiotapu geothermal field (Wilson et al., 2010) (Fig. 1). No associated fall deposit is preserved on land, although it is represented in the deep-sea record offshore from the North Island (e.g., Allan et al., 2008).

The ignimbrite is non-welded to strongly welded, and consists of multiple flow packages, which were erupted in a series of directional lobes (Briggs et al., 1993). The deposit is subdivided into an earlier erupted facies (Eu I), and a later erupted facies (Eu II). The latter contains densely welded fragments of recycled co-eruptive vitric tuff, which are absent in the Eu I deposits (Wilson, 1986). The eruption commenced with highly energetic, violent and hotter flows, generating a pumice-poor, fine grained ignimbrite that is often strongly welded. Later flows were cooler but less energetic and less violent, generating an upper pumice-rich ignimbrite (Briggs et al., 1993; Wilson, 1986).

3. Ongatiti clast types and mineralogy

Representative juvenile clasts displaying a wide variety of textures were sampled at locations covering both the lower (Eu I) and upper (Eu II) flow packages (Fig. 1), where large pumices with low degrees of post-depositional alteration or weathering could be found.

The Eu I material was primarily sampled from Ranginui Station, ~15 km west of Mangakino township at NZMG grid reference 2738052 m E 6307658 m N. Here the ignimbrite is ~25 m thick and poorly welded, forming craggy outcrops. Sample sites for the Eu II material include Tokahaere Rock at 2735352 m E 6333586 m N, Hinuera Quarry at 2746100 m E 6361400 m N and along Horahora Road at 2743859 m E 6351620 m N, north of Mangakino, in sintered to poorly-welded ignimbrite.

3.1. Juvenile clasts

Pumice textures vary greatly throughout the ignimbrite from crystal rich and dense clasts to highly vesicular clasts with fewer crystals. Pumices from the Eu I ignimbrite are poorly to highly vesicular and crystal rich (20–30%) containing crystal schlieren, and many are flattened to fiamme. A minor proportion of crystal-moderate to crystal-rich pumices display an 'adobe-type' texture (after Hildreth and Wilson, 2007), with a coarsely fibrous lineated fabric and crystal schlieren. Pumices from the upper flows are typically crystal-moderate to -rich, with a drawn out planar fabric and an abundance of glomerocrysts. In addition to 'normal' pumices, individual clasts (up to 24 cm) of microcrystalline material occur within the upper (Eu II) ignimbrite. Greater than 50% of pumices within Eu II ignimbrite also contain clots (average size ~2 cm) of visually identical material. Both individual clasts and clots are crystal rich (20–50%) with a vesiculated glassy matrix, the crystals being almost entirely plagioclase and amphibole grains with a consistent size (~1 mm) giving the material a distinctive 'salt and pepper'-like appearance (Fig. S1).

3.2. Lithic clasts

A wide range of lithic types are found within the Ongatiti ignimbrite, including andesite and rhyolite lavas, densely welded ignimbrite (including vitric, breadcrusted recycled Ongatiti material), biotite granite and granodiorite porphyry (Brown et al., 1998b; Krippner et al., 1998). The high proportion of lava clasts suggests that the volcanic pile engulfed by the Ongatiti vents comprised significant volumes of rhyolitic and andesitic lavas from earlier effusive episodes (Krippner et al., 1998). The compositional and isotopic data from granitoid lithic fragments are similar to the range displayed in the Ongatiti ignimbrite. However, although the granitoids may be geochemically related to the Ongatiti magma, they lack any interstitial glass phase and have common