Earth and Planetary Science Letters 313-314 (2012) 23–33

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

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

Systematic tapping of independent magma chambers during the 1 Ma Kidnappers supereruption

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ARTICLE INFO

Article history:
Received 5 August 2011
Received in revised form 2 November 2011
Accepted 7 November 2011
Available online 3 December 2011

Editor: R.W. Carlson

Keywords:
supereruption
multiple magmas
Kidnappers eruption
Taupo Volcanic Zone
eruption trigger
phreatomagmatic fall deposit

ABSTRACT

The 1.0 Ma Kidnappers supereruption (~1200 km^3 DRE) from Mangakino volcanic centre, Taupo Volcanic Zone, New Zealand, produced a large phreatomagmatic fall deposit followed by an exceptionally widespread ignimbrite. Detailed sampling and analysis of glass shards and mineral phases have been undertaken through a proximal 4.0 m section of the fall deposit, representing the first two-thirds of erupted extra-caldera material. Major and trace element chemistries of glass shards define three distinct populations (types A, B and C), which systematically change in proportion through the fall deposit and are inferred to represent three magma types. Type B glass and biotite first appear at the same level (~0.95 m above base) in the fall deposit suggesting later tapping of a biotite-bearing magma. Plagioclase and Fe–Ti oxide compositions show bimodal distributions, which are linked to types A and B glass compositions. Temperature and pressure (T–P) estimates from hornblende and Fe–Ti oxide equilibria from each magma type are similar and therefore the three magma bodies were adjacent, not vertically stacked, in the crust. Most hornblende model T–P estimates range from 770 to 840 °C and 90 to 170 MPa corresponding to storage depths of ~4.0–6.5 km. Hornblende model T–P estimates coupled with in situ trace element fingerprinting imply that the magma bodies were individually well mixed, and not stratified. Compositional gaps between the three glass compositional types imply that no mixing between these magmas occurred. We interpret these data, coupled with the systematic changes in shard compositional proportions through the fall deposit, to reflect that three independent melt-dominant bodies of magma contributed large (A, ~270 km^3), medium (B, ~90 km^3) and small (C, ~40 km^3) volumes (as reflected in the fall deposits) and were systematically tapped during the eruption. We propose that the systematic evacuation of the three independent magma bodies implies that there was tectonic triggering and linkage of eruptions. Our results show that supereruptions can be generated by near simultaneous multiple eruptions from independent magma chambers rather than the evacuation of a large single unitary magma chamber.

1. Introduction

Reconstructing the pre- and syn-eruptive processes that occur in silicic magma chambers during exceptionally large explosive eruptions (particularly 'supereruptions', $>10^{15}$ kg $\approx$ 450 km^3 of magma; e.g., Miller and Wark, 2008; Self, 2006; Sparks et al., 2005) continues to be a fundamental challenge in understanding how such vast bodies of magma are generated, stored and ultimately erupted. Generalised models for large silicic magma chambers (e.g., Bachmann and Bergantz, 2008; Hildreth, 1981, 2004; Shaw, 1985; Smith, 1979) envisage them to be single unitary bodies, with crystal-richer roots ('mush zones') that are not erupted except under unusual circumstances. Those eruptions involving rhyolitic compositions of any significant size (>1 km^3) in the high-silica rhyolite grouping of Hildreth (1981) are generally considered to be zoned in chemical or physical properties, with those zonations inversely reflected in the deposits (Bachmann and Bergantz, 2008; Smith, 1979). Crystal-poorer, more evolved magmas typically are erupted first, followed by crystal-richer, less evolved magmas, with gradients in crystal content matching gradients in chemical and mineralogical properties (e.g., Hildreth and Wilson, 2007). Where compositions cluster into discrete groups, such distinct magmas are generally inferred to be genetically related and modelled as layers in single chambers (e.g. Schuraytz et al., 1989; Streck and Grunder, 1997).

Recent studies have shown, however, that such models may be too simple for many examples, both small and large. The 27 ka Oruanui rhyolite shows compositional variability, but the different compositions were not systematically tapped during the eruption, and compositional variations in mineral and quartz-hosted melt inclusions show that the melt-dominant body was thoroughly stirred prior to eruption (Liu et al., 2006; Wilson et al., 2006). Single eruptions may tap two or more compositionally independent magma bodies in the

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doi:10.1016/j.epsl.2011.11.006

shallow crust (e.g., Briggs et al., 1993; Shane et al., 2007, 2008; Smith et al., 2004), and paired eruptions can occur where the tectonic adjustment from one eruption serves to trigger another eruption from nearby vents (e.g., Gravley et al., 2007; Nairn and Kohn, 1973).

In addition, in arriving at compositional information about silicic eruption deposits, there is a wide variability in the quality of material available. Ideally, individual juvenile clasts (pumice, in most cases) are sampled from all stratigraphic levels, but this ideal is seldom achievable. In particular, the fine-grained products of phreatomagmatic eruptions pose challenges because of the scarcity of large-enough pumice clasts and the volumetric dominance of fine-grained widespread fall deposits that are prone to erosion. Here we present field and geochemical data from the ~1 Ma Kidnappers eruption deposits in the Taupo Volcanic Zone (TVZ) of New Zealand. In this case, the stratigraphic controls are limited to the observation that at all localities the ignimbrite (non-welded and with fresh pumice) overlies and is hence postdates the substantially larger fall deposit (in which clasts >1–2 cm are absent). We thus use glass and mineral chemistry from the fall deposit to track compositional variations in the eruption products and infer the existence of multiple magma bodies that were systematically tapped during the first two-thirds of the eruption.

2. Geological background

The TVZ has been the dominant focus of volcanism in the central North Island of New Zealand since ~2 Ma. It is a <60 km wide, NNE-trending region of volcanism and associated extension forming the southern, continental continuation of the Tonga–Kermadec arc, associated with westward subduction of the Pacific plate beneath the Indo-Australian plate (Cole and Lewis, 1981: Fig. 1). In the ~120 km long, rhyolite-dominated central TVZ, >16,000 km^3 has been erupted since ~1.6 Ma in at least 25 caldera-forming and numerous other smaller eruptions from eight volcanic centres (Houghton et al., 1995; Wilson et al., 1995a, 2009).

The Kidnappers eruption is the second largest TVZ eruption known, dated at ~1 Ma by a variety of techniques, including $^{40}Ar/^{39}Ar$ dating and linking to the geomagnetic polarity timescale through its occurrence towards the top of normally magnetised deposits of the Jaramillo Subchron (Black, 1992; Wilson et al., 1995b). Kidnappers deposits consist of three components. There is a voluminous phreatomagmatic fall deposit, recorded across the North Island and for >1000 km eastwards across the Pacific Ocean floor (Carter et al., 2004; Ash A of Ninkovich, 1968; CJNW unpublished data: Fig. 1). This fall deposit is overlain by an exceptionally widespread non-welded ignimbrite that covers ~45,000 km^2 (Wilson et al., 1995b; Fig. 1). In addition, a >1.8 km thickness of poorly-welded but hydrothermally altered tuff, inferred from U–Pb age determinations on zircon to relate to this eruption, has been drilled near Mangakino township (Wilson et al., 2008), within the area identified as a composite collapse caldera for this and other eruptions from the Mangakino volcanic centre (Rogan, 1982; Stern, 1979; Wilson et al., 1984). The Kidnappers eruption was followed by a short period of erosion before eruption of the Rocky Hill ignimbrite, also from Mangakino, and we infer that the two eruptions collectively contributed to a composite deposit of primary and reworked volcaniclastic material that is mapped as the Potaka Tephra (e.g., Alloway et al., 2005; Carter et al., 2004; Shane, 1994).

Volumes of the Kidnappers eruption products are problematic to estimate because of extensive erosion and/or burial of the deposits. Limited thickness data from on land (CJNW unpublished data) and marine cores (Carter et al., 2004) show that the fall deposit is similar in size to the 340 ka Whakamaru eruption fall deposit for which a bulk volume of ~700 km^3 (~400 km^3, DRE) is estimated by Froggatt et al. (1986). The Kidnappers ignimbrite bulk volume is estimated at ~450 km^3 (equivalent to ~200 km^3, DRE) by Wilson et al. (1995b). An unknown (but clearly substantial) volume of material is represented by intracaldera material (Wilson et al., 2008) and if generalised models (e.g. Lipman, 1984; Mason et al., 2004) suggesting an approximately 1:1 relationship for the relative volumes of intra- versus extra-caldera material are adopted, then an overall dense-rock equivalent volume for the Kidnappers eruption of ~1200 km^3 is inferred. At worse, these estimates may carry an uncertainty of ±50% (cf. Hildreth, 1981, his Fig. 1). The fall deposit thus accounts for about two thirds of the extra-caldera volume of material.

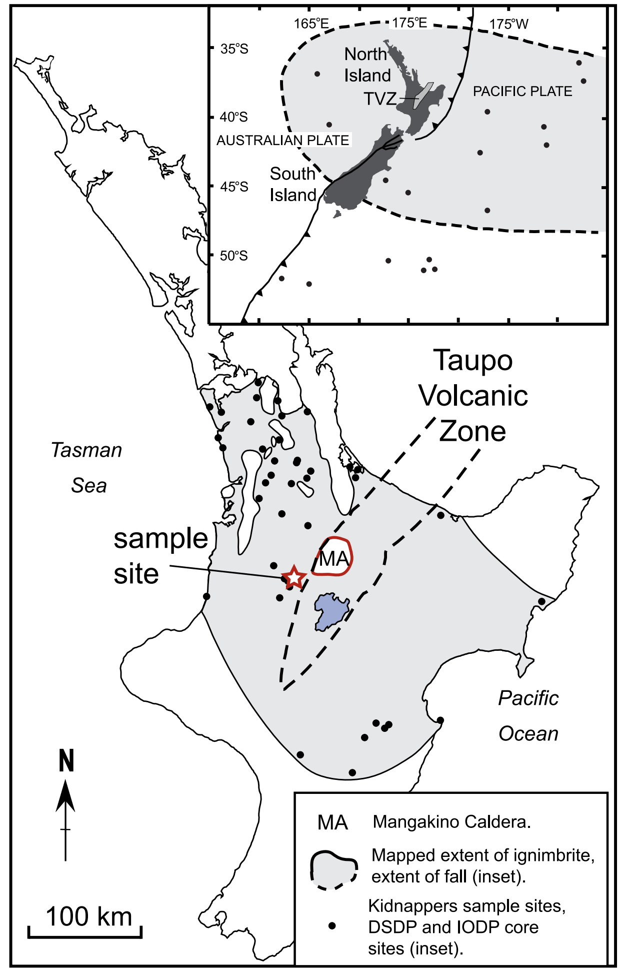

Fig. 1. Map of North Island, New Zealand, showing the Taupo Volcanic Zone (TVZ) and approximate location of Mangakino caldera (MA) on the western margin of the TVZ. The star marks the proximal fall deposit location. Shaded area defines the mapped extent of the Kidnappers ignimbrite (updated from Wilson et al., 1995b). Inset shows approximate extent of the Kidnappers fall deposit estimated from the offshore core record (adapted from Carter et al., 2004).

A 4.0 m section of the Kidnappers fall deposit, located approximately 30 km southwest of the Mangakino caldera rim on Pukemako Road at NZMG grid reference 2723847m E, 6289997m N (Fig. 1), was sampled for this study. This site was chosen because the fall deposit here is the thickest that has been found. It rests on a thick palaeosol developed on the 1.18 Ma Ahuroa ignimbrite and is overlain quasi-conformably by the slightly erosive base of the Kidnappers ignimbrite. The fall deposit is multiply bedded and poorly sorted, with upward increases in the abundance of accretionary lapilli and pumice sizes (to a maximum of 1–2 cm long).

3. Methods

3.1. Sample preparation and analytical techniques

Bulk samples from 11 selected levels in the 4.0 m fall deposit section were disaggregated and rinsed in water, then wet sieved into