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Rapid assembly and rejuvenation of a large silicic magmatic system: Insights from mineral diffusive profiles in the Kidnappers and Rocky Hill deposits, New Zealand

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A B S T R A C T

The timescales over which magmas in large silicic systems are reactivated, assembled and stored remains a fundamental question in volcanology. To address this question, we study timescales from Fe–Mg interdiffusion in orthopyroxenes and Ti diffusion in quartz from the caldera-forming 1200 km^3 Kidnappers and 200 km^3 Rocky Hill eruptions from the Mangakino volcanic centre (Taupo Volcanic Zone, New Zealand). The two eruptions came from the same source area, have indistinguishable $^{40}Ar/^{39}Ar$ ages ($\sim$1.0 Ma) and zircon U–Pb age spectra, but their respective deposits are separated by a short period of erosion. Compositions of pumice, glass and mineral species in the collective eruption deposits define multiple melt dominant bodies but indicate that these shared a common magmatic mush zone. Diffusion timescales from both eruptions are used to build on chemical and textural crystal signatures and interpret both the crystal growth histories and the timing of magma accumulation. Fe–Mg interdiffusion profiles in orthopyroxenes imply that the three melt-dominant bodies, established through extraction of melt and crystals from the common source, were generated within 600 years and with peak accumulation rates within 100 years of each eruption. In addition, a less-evolved melt interacted with the Kidnappers magma, beginning $\sim$30 years prior to and peaking within 3 years of the eruption. This interaction did not directly trigger the eruption, but may have primed the magmatic system. Orthopyroxene crystals with the same zoning patterns from the Kidnappers and Rocky Hill pumices yield consistently different diffusion timescales, suggesting a time break between the eruptions of $\sim$20 years (from core–rim zones) to $\sim$10 years (outer rim zones). Diffusion of Ti in quartz reveals similarly short timescales and magmatic residence times of $<$30 years, suggesting quartz is only recording the last period of crystallization within the final eruptible melt. Accumulation of the eruptible magma for these two, closely successive eruptions was accomplished over centuries to decades, in contrast to the gestation time of the magmatic system of $\sim$200 kyr, as indicated by zircon age patterns. The magmatic system was able to recover after the Kidnappers eruption in only $\sim$10–20 years to accumulate enough eruptible melt and crystals for a second $\sim$200 km^3 eruption. Our data support concepts of large silicic systems being stored as long-lived crystal mushes, with eruptible melts generated over extraordinarily short timescales prior to eruption.

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1. Introduction

Establishing the timescales of magmatic processes associated with large explosive eruptions provides important insights into the dynamics of large-scale crustal magmatic systems and the processes that lead up to eruption. There are two contrasting, but complementary, approaches to measuring these time scales, both of which utilise mineral phases in the eruption products. The first involves direct age dating of crystallization events through such techniques as U-series or U–Pb dating of suitable accessory mineral phases, such as zircon, allanite, or titanite (e.g. Schmitt, 2011) or the use of parent-daughter isochrons, such as Rb/Sr techniques in feldspars (e.g. Davies et al., 1994). The second approach is that of indirect age dating through diffusion modelling of inferred step-changes in compositional characteristics in minerals (e.g. Costa et al., 2008; Chakraborty, 2008; Costa and Morgan, 2010). Rather than dating the age of crystals themselves, this approach measures the time elapsed at magmatic temperatures following periods of re-

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Table 1
Summary of orthopyroxene textural populations.

Groups and samples	Temperature	f_{O_2} (ΔNNO)	Normal	Reverse	Unzoned	Patchy	Dark outer
Kidnappers							
KI-3 (low-SiO_2) P1655, P17XX	820 °C	0.1	34.0%	7.6%	51.4%	6.9%	41.0%
KI-1 (mid-SiO_2) P1646, P1649, P2011	785 °C	0.0	53.1%	3.1%	42.2%	1.6%	5.5%
KI-2 (high-SiO_2) P1607, P1609, P2006, P2015	780 °C	0.2	76.2%	1.2%	15.2%	7.3%	2.4%
Rocky Hill							
RH-1 (normal) P2000, P2029, P2042, P2049, P2050	795 °C	0.1	54.7%	6.6%	38.1%	0.6%	13.2%
RH-2 (high SiO_2) P2046	765 °C	0.0	94.3%	1.1%	4.6%	0.0%	1.1%

Temperatures presented were used to calculate orthopyroxene diffusive timescales from each compositional group from the Kidnappers and Rocky Hill.

newed growth and formation of crystal zonation within individual grains.

For those eruptive units where both of these approaches have been undertaken, there is an apparent contrast between the respective results. Crystal-specific ages indicate histories of typically 10^3 to $> 10^5$ years, whereas diffusion modelling yields estimates in the 10^1 to 10^3 years range (e.g. Turner and Costa, 2007; Cooper and Kent, 2014). This contrast can be linked to the inference that the chemical processes leading to these magmas (and growth of their crystal cargo, particularly the zircons that are dated) can be prolonged and magma within large silicic systems may be stored at near-solidus conditions for long periods of time (Cooper and Kent, 2014). This concept involves the waxing and waning of a crystal-rich, melt-poor (mush) system and the generation of large volumes of melt of given composition through fractionation, controlled by the rates at which material and heat are added and heat can be lost (e.g. Hildreth, 2004; Bachmann and Bergantz, 2004). On the other hand, processes involved in the mobilisation and extraction of that melt into eruptible bodies can occur much more rapidly because they only involve the physical transportation of melt ± crystals (Wilson and Charlier, 2009; Gualda et al., 2012; Allan et al., 2013; Barker et al., 2016).

The textures, compositions and thicknesses of growth zones within crystals can be used to discriminate between different magmatic processes responsible for the zonation (Saunders et al., 2012; Allan et al., 2013; Kahl et al., 2013). Each crystal interior may have a diverse and complex growth history, but zoning features that are common to a substantial proportion of all crystals allow for the distinction to be made between localised versus system-wide crystal histories. In the case of the Oruanui and post-Oruanui rhyolites from Taupo volcano the zoning in phenocryst phases records common magmatic histories and suggests rapid rejuvenation of crystal mushes and melt accumulation (Allan et al., 2013; Barker et al., 2016). In addition, there may be disparities in the timescales estimated from different phases recording seemingly common processes (e.g. Chamberlain et al., 2014) and so if zoning within the crystals permits, it is important to consider the timescales from multiple phases. Here we present pre-eruptive timescales for assembly of the final erupted melt-dominant bodies inferred from Fe–Mg interdiffusion in orthopyroxene and Ti diffusion in quartz from pumices in two eruptions, the Kidnappers and Rocky Hill events from Mangakino volcanic centre, New Zealand (Tables 1 and 2). We also use the difference in timescales from common growth zones within orthopyroxenes from the Kidnappers and Rocky Hill deposits to constrain the time break, inferred from field evidence to be geologically short, between the two eruptions.

2. Kidnappers and Rocky Hill eruptions

The Kidnappers and Rocky Hill eruptions occurred from the Mangakino volcanic centre, a composite caldera system in the Taupo Volcanic Zone, New Zealand (Fig. 1; Wilson et al., 2009). The Kidnappers eruption (~1200 km^3 DRE) generated a large, fine-grained phreatomagmatic fall deposit (Carter et al., 2004;

Table 2
Summary of quartz textural populations.

Groups and samples	Temperature	Dark rim	Light rim	No significant change
Kidnappers KI-2 (P2006)	780 °C	80%	7%	13%
Rocky Hill RH-1 (P2050)	795 °C	19.5%	61%	19.5%

Textural classification in based on CL intensities. Temperatures presented were used to calculate quartz diffusive timescales.

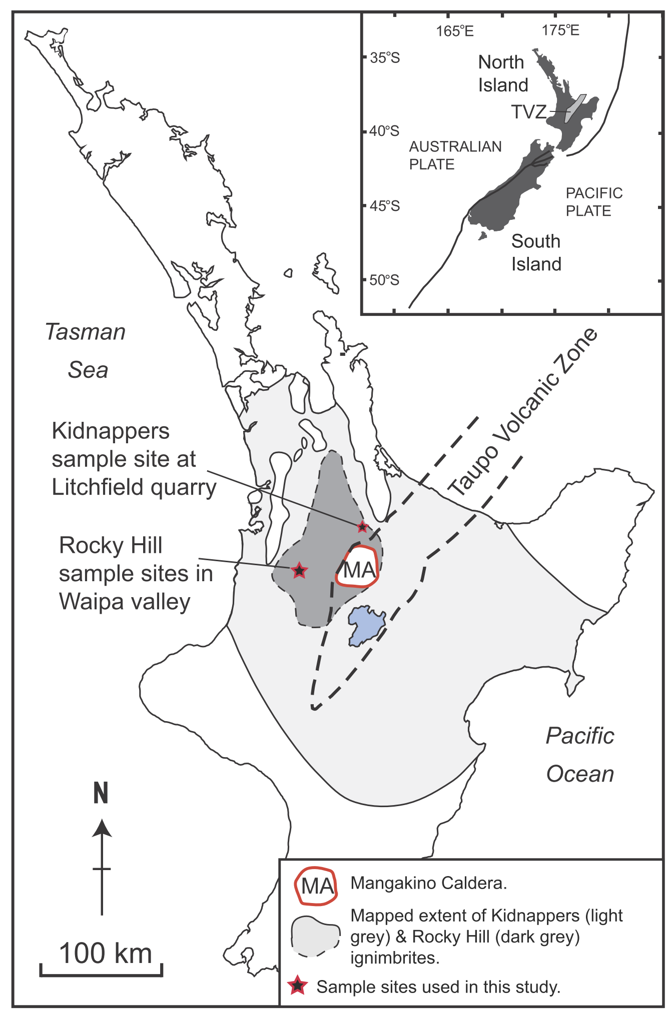

Fig. 1. Map of the North Island, New Zealand showing the location of the Mangakino caldera and extent of the Kidnappers and Rocky Hill ignimbrites. Sample site locations used in this study are shown. Modified from Cooper et al. (2016).

Cooper et al., 2012), followed by an exceptionally widespread, non-welded ignimbrite (Wilson et al., 1995). It was followed, after a short interval of erosion, by the ~200 km^3 Rocky Hill eruption

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