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Sequential eruption of alkaline and sub-alkaline magmas from a small monogenetic volcano in the Auckland Volcanic Field, New Zealand

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A B S T R A C T

Rangitoto Volcano is the youngest and largest eruptive centre in the monogenetic intraplate Auckland Volcanic Field (AVF). The stratigraphy of Rangitoto pyroclastic deposits that have been preserved in swamps on nearby Motutapu Island and in Lake Pupuke on the mainland reveals that the volcano erupted twice; radiocarbon dating of 10 samples from the two tephra units in the swamps indicates eruption ages of 553 ± 7 and 504 ± 5 Cal years BP, for the lower and upper tephra layers, respectively. Geochemistry of the lava field and various scoria cones on Rangitoto Island itself reveals two distinct compositional groups: an alkaline olivine basalt group (that correlates geochemically with the lower tephra layer) and a group that is sub-alkaline and transitional to tholeiite (that correlates geochemically with the upper tephra layer). Based on this data, we infer that, following a phreatomagmatic vent-clearing phase, the early magmatic eruption of Rangitoto Volcano was Strombolian in character and produced an alkaline olivine basalt scoria cone and an associated thick ash deposit on nearby Motutapu Island. This was followed by a time gap of up to several decades, after which a second eruptive phase built the current summit scoria cone together with an encircling lava field. We suggest this later, sub-alkaline eruptive period was associated with the deposition of the thin upper tephra layer on Motutapu Island. The two suites of Rangitoto samples are chemically quite distinct, and each is associated with a distinct parental composition. Trace element modelling indicates the alkaline and sub-alkaline parental melts could have been derived by ~1 and 6 wt.% partial melting of an anhydrous garnet peridotite source at ~80 and 65 km depth, respectively. The compositional range within each suite is similar, and can be explained by mainly olivine together with minor clinopyroxene fractionation within a relatively simple conduit system in which mixing and mingling were not important. Significant olivine fractionation (<25%) suggests that the magma may have spent some time in the upper conduit during ascent. This contrasts with a recently published model for the Crater Hill centre in the AVF, in which deep-seated fractionation of clinopyroxene followed by relatively rapid ascent to the surface has been invoked to explain the compositions seen there. The polycyclic nature of Rangitoto and in particular the reuse of the conduit system after a period of quiescence have implications for the concept of monogenetic volcanism. There are also implications for hazard assessment, such that when a future eruption occurs in the AVF, it will be necessary to consider the conduit a possible pathway for another eruption for up to several decades afterwards.

1. Introduction

Monogenetic basaltic volcanic systems are characterised by the eruption of discrete small-volume magma batches, typically in a single episode, lasting between days and months to several years. This, together with their dispersed plumbing networks, leads to their expression at the Earth's surface as fields of small volcanoes. The rocks forming individual volcanoes in monogenetic fields typically show a range of chemical compositions which in some examples is comparable to those in entire regions (e.g. Harpp, 1995; Rubin et al., 2001; Maclennan et al., 2003). Detailed studies of individual volcanoes in monogenetic fields have demonstrated that there is commonly a systematic relationship of chemical composition to stratigraphic position and therefore to time in an eruption sequence (e.g. Francis and Ludden, 1990; Glazner et al., 1991; Carracedo et al., 1992; Garcia et al., 2000; Reiners, 2002; Strong and Wolff, 2003; Smith et al., 2008; Blondes et al., 2008; Brenna et al., in press) but, intriguingly, the nature of compositional trends can be completely different in different volcanoes. Such compositional variations reflect processes acting on primary magmas during their segregation from source and passage through the conduit system. In contrast, polygenetic volcanoes show complex patterns of compositional variation that can be attributed to larger magma volumes, more complex plumbing

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systems and interaction with the crust in magma storage chambers (Walker, 2000; Canon-Tapia and Walker, 2004). Studies of basaltic monogenetic fields in western USA have suggested that some monogenetic cones may actually be polygenetic and/or polycyclic, involving multiple eruptions separated by tens to hundreds of thousands of years (e.g. Turrin and Renne, 1987; Renault et al., 1988; Wells et al., 1990; Bradshaw and Smith, 1994). Thus it appears that the generalised concept of monogenetic volcanism includes a range of phenomena from simple eruption of discrete magma batches through polycyclic behaviour involving more than one magma batch and ultimately to polygenetic systems.

The Auckland Volcanic Field (AVF) is a young monogenetic intraplate volcanic field made up of about 50 small basaltic volcanoes within an area of approximately 30 × 20 km centred on Auckland City in northern New Zealand. Roughly 4 km^3 (3.4 km^3 Dry Rock Equivalent, DRE) of material has been erupted in the AVF since volcanic activity commenced approximately 250 ka years ago (Kermode, 1992; Allen and Smith, 1994; Molloy et al., 2009). The AVF is similar to other volcanic fields regionally and globally in terms of chemical composition, volumes produced and longevity. The field lacks any clear spatio-temporal patterns or recurrence intervals but recent tephrochronology, paleo-magnetism and Ar–Ar dating studies have shown temporal clustering of some vents which suggests irregular patterns of eruptive activity (Molloy et al., 2009; Cassidy, 2006; Cassata et al., 2008 and references therein). Further, there is emerging evidence for polycyclic behaviour in some of the larger volcanoes of the AVF. For example, Rangitoto Volcano, the largest and most recent eruption to occur in the field, is the result of two compositionally and temporally discrete magma batches that appear to have shared the same conduit system. The occurrence of these distinct magma batches raises questions about the way that partial melting and magma extraction processes operate in the upper mantle and about the timescales involved. Here we present the results of a detailed study of the geochemistry and geochronology of Rangitoto Volcano as the basis for a model to explain the processes of magma generation and rejuvenation in a monogenetic volcanic system.

2. Rangitoto Volcano

Rangitoto Island (Fig. 1) is a near symmetrical volcano rising ~260 masl. It is ~6 km at its widest and has an estimated bulk volume of 1.78 km^3. The summit region consists of a central scoria cone containing a 60 m deep, 150 m wide crater that is flanked to the north and south by complex scoria mounds and ridges (Fig. 2) inferred to represent the remnants of older craters destroyed by successive eruptive events and referred to as the North and South Cones. The lower flanks of the volcano are composed of a lava field that dips gently from ~12° near the base of the scoria cone to ~4° near the coast. The lava field is composed mostly of rough, a′a textured lava together with minor pahoehoe flows. Pyroclastic phases of the eruptions that built Rangitoto were dispersed mainly to the northeast, and the resulting record is revealed in ash sequences on adjacent Motutapu Island, where a prominent 20 to 50 cm thick, dark grey to black deposit of pyroclastic material mantles a large portion of the island (Fig. 1). Archaeological excavations at the Sunde Site (Fig. 1) have revealed that cultural layers were buried by this tephra layer (Scott, 1970); casts of human and dog footprints preserved in the tephra also provide evidence for human habitation on Motutapu before and after the eruption. The ash partially filled and blocked pre-existing stream drainages, and resulted in the formation of numerous small swamps; it is in these that the details of the Rangitoto eruption sequence are revealed.

In this study we used vibracoring methods to collect 10 cores from four swamps on Motutapu Island to define a detailed stratigraphic record of the eruption sequence and provide tephra samples for geochemical analysis. We also collected lava and scoria samples from all stages of the eruption represented by surface outcrops on Rangitoto Island itself.

3. Geochronology and eruptive history

The swamps on Motutapu Island that were selected for detailed study were located both proximally and distally to the Rangitoto vents (Fig. 1). An effort was made to choose swamps that were wide and that lacked evidence of slope instability at their margins. Coring sites were located as close as possible to the middle of the swamps. Core logging revealed that the stratigraphy of the sediments across all the swamps was consistent (Fig. 3). Prominent features of the swamp stratigraphy are two black medium to coarse sand sized tephra layers: a thin (c. <10 cm) upper unit and a thick (c. 20–100 cm) lower unit, separated by a layer of peat approximately 10–50 cm thick. Variations in the thickness of the discrete tephra layers reflect position relative to the north-easterly axis of dispersal, together with localised factors within each swamp.

Samples of twigs, charcoal and peat associated with the two tephra layers on Motutapu Island were selected for radiocarbon dating. Samples were cleaned thoroughly in distilled water, dried, and submitted to the University of Waikato Radiocarbon Dating Laboratory (5 samples) and Rafter GNS Science Radiocarbon Laboratory (5 samples) for analysis. The results are presented in Table 1, together with all other radiocarbon ages available for Rangitoto Volcano. Eight charcoal samples from the thick, lower tephra yielded ages ranging from 532 ± 17 Cal years BP to 893 ± 47 Cal years BP, with 7 ages falling within error of 549–580 Cal years BP (Table 1). These 7 ages representing the thicker lower tephra give a weighted mean age of 553 ± 7 Cal years BP (AD 1397) which is consistent with other radiocarbon age determinations available for the Rangitoto ash on Motutapu Island (Table 1; Lindsay and Leonard, 2009, and references therein). The oldest age of 893 ± 47 Cal years BP was excluded from the weighted mean calculations as it is interpreted to represent older organic material washed into the swamp at the time of tephra deposition. Two ages were obtained from peat from above and within the upper tephra layer; 502 ± 11 and 504 ± 6 Cal years BP, respectively (Table 1). A weighted mean of these two analyses yields an age of 504 ± 5 Cal years BP (AD 1446).

These ages (and errors) suggest that there was a gap of perhaps 30 to 60 years between the two ash-producing eruptions. This is consistent with the presence of laminated lake sediments between two tephra layers (2 and 1 mm-thick, at 28 and 27 cm depth, respectively) inferred to be from Rangitoto in a core from Lake Pupuke ~5 km to the west (Fig. 1; Horrocks et al., 2005), although the time gap between these layers estimated based on sedimentation rates is somewhat lower, at 5–22 years.

Based on the stratigraphic and geochronological data presented above we have reconstructed an eruption history for Rangitoto Volcano. The first eruption from Rangitoto commenced about 600 years ago. From present-day bathymetry, it is likely the magma erupted through sea water no more than 15 m in depth. The inferred position of the vent for this first eruption is north of the present summit and the ridges and peaks on the northern side of the Central Cone are thought to be remnants of this vent because of similarities in chemical composition. Interaction between magma and water probably resulted in an explosive phreatomagmatic eruption and the development of a tuff ring (Fig. 4A). Although a tuff ring has not been observed, it is inferred to exist beneath the lava field. Following this initial stage, Strombolian style activity resulted in the formation of a scoria cone (Fig. 4B) with a maximum height of ~200 masl, based on the known heights of the ridges and peaks representing the North Cone. Throughout these early stages of the eruption significant volumes of ash were dispersed toward the northeast and deposited on nearby Motutapu Island.