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Distal occurrence of mid-Holocene Whakatane Tephra on the Chatham Islands, New Zealand, and potential for cryptotephra studies

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Abstract

The Whakatane Tephra, a rhyolitic tephra erupted ca. 5500 cal. BP from Okataina Volcanic Centre, central North Island, has been identified on the Chatham Islands which lie ~900 km east of Christchurch, New Zealand. The visible tephra layer, ~5 mm in thickness and preserved within peat on Pitt Island, was identified using both radiocarbon dating and analysis of glass shards by electron microprobe. Whakatane Tephra is the first Holocene tephra to be identified on the Chatham Islands, and it is the most distal Holocene tephra yet recorded in the New Zealand region, being ~850 km from source. The Pitt Island occurrence extends the tephra's dispersal area markedly, by an order of magnitude, possibly to ~300,000 km^2. An estimated dispersal index (*D*) of approximately 10^5 km^2 indicates that the eruption generated a very high plinian column, possibly exceeding ~30 km in height, with strong winds blowing the ash plume southeastwards.This new discovery of distal Whakatane Tephra as a thin but visible layer strongly implies that cryptotephras are likely to bepreserved on the Chatham Islands and within adjacent ocean floor sediments. Therefore the potential exists to develop enhanced cryptotephrostratigraphic records from these distal areas, which in turn would help facilitate precise correlation via tephrochronology of palaeoenvironmental records (such as NZ-INTIMATE) from mainland New Zealand, the southwest Pacific Ocean, and the Chatham Islands.

1. Introduction

In New Zealand, the Taupo and Okataina volcanic centres in the central TaupoVolcanic Zone (TVZ, Fig. 1A) are the most productive Late Quaternary rhyolitic centres in the world (Wilson et al., 1995). They have produced >60 rhyolitic eruptions within the past ca. 60,000 years (Wilson et al., 2009; Lowe, 2011). Tephras from these eruptions form a comprehensive chronostratigraphic framework for Quaternary stratigraphic and palaeoclimate records in the

New Zealand region including the NZ-INTIMATE project (e.g., Alloway et al., 1993, 2007; Pillans et al., 1993, 2005; Newnham et al., 1999a, 2007; Lowe et al., 2008).

Tephra layers from some of the largest-volume eruptions are commonly encountered in distal settings. For example, tephra from the ca. 27,100 calendar (cal.) BP Kawakawa/Oruanui eruption (~530 km^3 dense rock equivalent,DRE) from Taupo Volcanic Centre (Wilson, 2001) has been identified>1500 km from source (Carter et al., 1995; Lowe et al., 2008). Another less voluminous but nevertheless widespread tephrais the ca. 17,600 cal. BP Rerewhakaaitu Tephra (~5 km^3 DRE) from the Okataina Volcanic Centre, known to occur at least 500 km from source (Newnham et al., 2003; Lowe et al., 2008). These and numerous other Quaternary-aged tephras have been described in cores of marine sediments around New Zealand, mainly to the east or northeast in the Pacific Ocean (e.g., Pillans and Wright, 1992; Carter et al., 1995, 2003; Alloway et al., 2005; Shane et al., 2006; Allan et al., 2008) and also, much less frequently, to the west in the Tasman Sea (e.g., Nelson et al., 1985; Carter et al., 2004).

Although Holocene-aged tephras have been described from a number of marine cores taken from sites within ~300 km of the TVZ, such as P69, MD97-2121, H209–H215, S794, S803, and the RR series (e.g., Kohn and Glasby, 1978; Stewart and Neall, 1984; Pillans and Wright, 1992; Carter et al., 1995, 2008; Shane et al., 2006), such tephras are rarely documented in cores taken from waters beyond ~300 km. Only two Late-Holocene eruptives, the Waimihia (ca. 3,400 cal. BP) and Taupo (ca. 232 AD) tephras, have been recorded ~560 km and ~660 km, respectively, from TVZ thus far (Carter et al., 1995). Allan et al. (2008) examined three cores from ODP Site 1123, ~1100 km east of New Zealand (Fig. 1C), but reported no Holocene tephras despite recording 70 visible tephra layers (each ~4 cm thickon average) within sediments dating back to ca. 1.8 Ma. Yet it is evident from observations of historic and modern ash clouds that such clouds, even from eruptions of quite low volume,

are very commonly blown long distances ranging from ~750 km to ~2500 km (e.g., Mt Tarawera, 1886; Mt St Helens, 1980; Mt Pinatubo, 1991; Mt Ruapehu, 1995-96), and ash from the eruptions of Mt Spurr (1992) and Klyuchevskoy (1994) travelled at least ~5000 km(Lowe, 2011). Most recently, tephra from the Icelandic Eyjafjöll eruptions of April-May in 2010, relatively minor in terms of volume, was distributed over much of Scandinavia and Europe as far as Siberia, more than ~8,000 km from source (Davies et al., 2010a).

Thus it seems highly likely that ash from many of the Holocenerhyoliticeruptions from central TVZ volcanoes (additional to Waimihia and Taupotephras) would have been delivered to and deposited in distal settings well over ~300 km from New Zealand. Consequently, the Chatham Islands, lying ~900 km directly east of Christchurch, New Zealand (Fig. 1A), and blanketed by extensive peat deposits, would seem to provide a very suitable, stable archive for recording distal tephra deposits either as thin, visible layers or as cryptotephras. Two relatively thick (≥~10 cm), visible tephra layers are already known: the Rangitawa (ca. 340 ka) and Kawakawa/Oruanuitephras (Holt et al., 2010). A third visible tephra layer, the mid-Holocene WhakataneTephra, ~5 mm in thickness,is preserved in peat on Pitt Island in the Chatham Islands group (Fig. 1B). This paper describes the identification of this distal tephra using compositional analysis of constituent glass shards via the electron microprobe and by dating peat contiguous with the layer using the radiocarbon (^{14}C) method. It discusses the significance of this occurrence, the most-distal Holocene tephra recorded for the New Zealand region, with respect to potential cryptotephra studies ofmarine cores around New Zealand and on the Chatham Islands. Alsoconsidered are some of the implications for ash dispersal and for volcanic hazards in distal locations such as the Chatham Islands, and some reasons for the current paucity of Holocene tephras in the distal marine record.

2. Whakatane Tephra and its occurrence on Pitt Island

The Whakatane Tephra (WT) was erupted during the Whakatane eruption episode from the Haroharo Linear Vent Zone (HLVZ, Fig. 1A) within the Okataina Volcanic Centre (Nairn, 2002; Kobayashi et al., 2005; Smith et al., 2006) at ca. 5500 cal.BP. With a total volume estimated at 11.3 km^3(DRE), the eruption involvedthree different batches of magma (Kobayashi et al., 2005). Ash eruptedduring the plinian phases was distributed mostly to the north, east, and southeast of source, with the main axis of dispersal being towards the southeast (Nairn, 2002; Kobayashi et al., 2005). Until now, the most-distal occurrence of WTknown was within ocean sediments of the MD97-2121 core (Carter et al., 2002, 2008), located~280 km southeast of source (Fig. 1C).

The Chatham Islands are located ~850 km southeast and essentially downwind of the HLVC and TVZ (Fig. 1A). A volcanic ash layer, correlated here with WT, has been identified at one locality on Pitt Island, the smaller of the two inhabited islands in the Chatham Islands group (Fig. 1B). WT occurs as a thin (~5 mm), discontinuous layer within peat overlying pre-Quaternary volcanic deposits (Fig. 2). The Kawakawa/Oruanui tephra occurs approximately 30 cm below the WTon the contact between the basal peat and the pre-Quaternaryvolcanics. At this site, the WT is composed almost entirely of very fine-ash-sizedrhyolitic(silica-rich) glass shards. The paucity of crystals is attributed to the earlier fallout of these, because of their density,from the Whakatane ash plume as it was blown towards the Chatham Islands.

3. Age of Whakatane Tephra and correlation by electron microprobe analysis of glass

A radiometric ^{14}Cage was obtained on a sample of peat enclosing the tephra (i.e., slices of peat ~1-cm thick were taken from directly beneath and above the layer and combined into a single sample). The sample was processed (acid-base-acid pre-treatment) and dated at the

University of Waikato Radiocarbon Dating Laboratory using benzene-based liquid scintillation spectrometry. It returned a conventional ^{14}C age of 4806 ± 41 ^{14}C BP (Wk-28291). Calibration of the age using SHCal04 (McCormac et al., 2004) via OxCal4 gave a calibrated (calendar) age range of 5326 to 5589 cal. BP (95.4% confidence limit), with a mean age of 5479 ± 79 cal. BP (Fig. 3). This age is statisticallyidentical to the age of 5530 ± 60 cal. BP (2σ) for the WT obtained by flexible age-depth modelling (similar to wiggle-matching)of a sequence of ages within the Kaipobogtephra sequence in eastern North Island against IntCal04 usingOxCal (Hajdas et al., 2006). It also matches the age of 5520 ± 45 cal. BP (2σ), with a 'best' age estimate (maximum *a posterior* estimator) of 5490 cal. BP, obtained by Lowe et al. (2008) for WT in the same sequence using Bpeat(Blaauw et al., 2007). Other ^{14}C ages on WT include those summarised by Lowe (1986), Froggatt and Lowe (1990), and Nairn (2002).

Analyses by electron probe microanalysis (EPMA) were undertaken on individual glass shards from the tephra using an energy dispersive (EDS) Jeol JXA-840A electron microprobe at the University of Auckland's School of Environment. The analyses were collected using a Princeton GammaTech Prism 2000 Si (Li) EDS X-ray detector, a 20-µm defocused beam to minimise loss of sodium and potassium, an accelerating voltage of 12.5 kV, a beam current of 600 pA, and 100 seconds live count time. An Astimex^{TM}albite standard was analysed regularly (under a 2-µm focussed beam) before and after analysis of the glass samples to ensure a consistent level of performance by the microprobe. The resulting analyses, recalculated to 100% on a volatile-free basis, are presented in Table 1. Analyses of glass shardsof the three magmas erupted during the Whakataneepisode are presented in Table 1, along with analyses from two other Okataina-derivederuptives for comparison (discussed below).

Prior to the return of the ^{14}Cage, the tephra on Pitt Island was tentatively correlated to either the KaharoaTephra (1314 ± 12 AD) or the RotoruaTephra (type T2 magma) (ca. 15,400 cal. BP) eruptions from OVC (Lowe et al., 2008) because of general similarities in FeO, CaO and K_2O concentrations especially (Fig. 4A; Table 1), and also partly because of its proximity to the peat surface (Fig. 2). However, in light of the ^{14}C age these two options were ruled out. The glass chemistry major element data (rhyolitic on the basis of SiO_2 content) from the Pitt Island sample match closely with those of the Makatiti pyroclastic eruptives (column M in Table 1) of the Whakatane eruption episode (Fig. 4B). The Makatiti magma batch was the most voluminous of the three batches involved in the eruption episode, with ~10 km^3 (DRE) of this 'M-type' magma being erupted (2.3 km^3 as pyroclastics, 7.5 km^3 as lava) (Kobayashi et al., 2005). The Makatitimagma batch was also the main source for the Whakatane eruption episode fall deposits which total ~2.55 km^3 (DRE) in volume (Kobayashi et al., 2005; Shane et al., 2008). Analyses (by EPMA) of glass in WT deposits from locations beyond the main vent area also match the Makatitieruptives, for example at Kaipo bog (60 km southeast of source), Lake Poukawa (180 km south-southeast of source), Kopouatai bog (120 km north-northeast of source), and in *Roger Revelle* core RR107 (180 km northeast of source) (Fig. 1C) (Lowe et al., 1999; Gehrels et al., 2006; Shane et al., 2006, 2008).

Thus the combination of the^{14}Cage and glass major element composition confirms the identity of the tephra on Pitt Island as WT. Elsewhere in New Zealand, ferromagnesian mineral assemblages are employed as another means of tephra identification, and a characteristic feature of the WT is the presence of abundant cummingtonite (Froggatt and Lowe, 1990; Lowe et al., 2008), but the absence of free crystals within the Pitt Island deposit precluded the use of this diagnostic tool.

4. Discussion and implications

The discovery of WT on Pitt Island, even at ~5 mm in thickness, is of considerable significance. Its occurrence in such a distal location ~850 km from source has implications for several different fields of study including eruption dynamics and volcanic hazard interpretation as well as informing meteorological conditions during its eruption. But perhaps of most significance is that the distal occurrence of WT demonstrates that new insight into documenting the dispersal of tephras across the wider New Zealand/southwest Pacific region is potentially attainable. These points are discussed in turn below.

The presence of the ash of measurable thickness ~850 km from TVZ may be used to improve calculations of eruption column height and other eruption characteristics including dispersal index and estimates of volume (e.g., Pyle, 1989; Bonadonna and Houghton, 2005; Macedonio et al., 2005). Although the WT thickness on Pitt Island is only ~5 mm, and it is but one site, the area over which WT was potentially deposited has been increased enormously, especially if the distribution formed the pattern of a fan, widening with increasing distance away from source, rather than as a narrow ellipse (Fig. 1C). The area encompassed by the inferred 1-cm isopach depicted in Fig. 1C is ~230,000 km^2, and that of the inferred 0.5-cm isopach is ~390,000 km^2. If these isopachs are assumed to be roughly correct, then the area encompassed by the tephra within the 0.5-cm isopach is an order of magnitude greaterthan that previously recorded for the fall deposits: Nairn (2002) noted the on-land area (within the 10-cm isopach on North Island) to be >16,000 km^2.

The area, *D*, dispersal index, enclosed by the $0.01T_{max}$isopach (where T_{max} is the maximum thickness of the fall deposit) (Houghton et al., 2000), is indicative of the dispersive power of an eruption. Assuming that T_{max} for the WT is 150 cm on the basis of data in Kobayashi et al. (2005, p. 472), then the ~1-cm isopachin Fig. 1C crudely approximates

$0.01T_{max}$ (~1.5 cm). On this basis, an approximate dispersal index (*D*) of around ~200,000 km^2 may be estimated using the area of the ellipse for the inferred 1-cm-isopach noted above. Comparison with *D* values in the literature (e.g., Walker, 1981a) indicate that this value for the WT, if approximately correct, implies that the eruption was very powerful indeed and had a very high eruption column (possibly between 30 and 50 km, and with an extensive plume) because the dispersal area is mainly a function of the column height and the atmospheric wind regime (e.g., Walker, 1981b; Pyle, 2000). Strong winds would have blown the ash plume southeastwards, perhaps for a number of days (as deduced from studies on other rhyolitic eruptions, e.g., Nairn et al., 2001).

As well, the volume of ~2.55 km^3 (DRE) for all the Whakatane pyroclastic deposits is demonstrably a minimum estimate given the new knowledge that measurable fallout extended to Pitt Island, well beyond the outermost (and entirely land-based, i.e., on North Island) 10-cm isopach limit of Pullar (1973) that was used by Kobaysahi et al. (2005) in their volume calculations.

A second consideration of the occurrence of WT is its implications for volcanic hazard assessment in the Chatham Islands. Although the threat from thick tephra fallout derived from extremely large-scale super-eruptions, such as the Kawakawa/Oruanui event, is now well documented (e.g., Manville and Wilson, 2004a; Wilson, 2008; Holt et al., 2010), that of eruptions much smaller in volume has been significantly underestimated (e.g., Payne et al., 2008). As the presence of the WT indicates, very fine volcanic ash from an eruption relatively small in volume has clearly made it to the Chatham Islands. Although such a thin, fine-grained dusting of tephra might be barely noticeable at the time of deposition, it nevertheless would presentseveral threats including putting air travel at risk (e.g., Newnham et al., 1999b;Folch and Sulpizio, 2010). It is also a significant thoracic or respiratory hazard for residents and animals with the potential to cause acute and chronic respiratory diseases

(Horwell and Baxter, 2006). Newnham et al. (2010) demonstrated that diffuse fine ash poses a risk to respiratory health at greater distances from an eruption than previously perceived. They identified a significant increase in respiratory-related mortality in Auckland and Hamilton in North Island as a possible consequence of the effects of diffuse, fine-grained ash fallout at these locations, which had been barely or not observed, from the 1996 eruptions of Mt Ruapehu. The hazard arises because the finest 'respirable' fraction of erupted tephra (mainly shards of glass), defined as grains <4 μm in diameter (Horwell and Baxter, 2006), with potentially hazardous physicochemical properties, is dispersed the greatest distance. Such respirable particles can penetrate the alveolar region of the lung where chronic respiratory diseases such as silicosis are activated (Horwell, 2007). Particles <10μm in diameter, the 'thoracic' fraction, are also hazardous, and may enter the bronchiolescausing lungirritation, inflammation, asthma, and bronchitis, and there is a strong correlation between the amounts of <10 μm and <4 μm material in a wide range of ash types including rhyolitic ash (Horwell, 2007). Ultra-fine particles (<2.5 μm in diameter) and those in the nanoparticle range (< 0.5 μm) may have even greater disease-causing potential (Horwell, 2007). At such locations where diffuse, very fine-grained ashfall is barely or not visibly discernible, as would likely occur in the Chatham Islands, individuals would therefore not perceive any risk and hence preventative measures (e.g., use of face masks) seemingly could be ignored despite those with poor respiratory health being at substantial risk (Horwell, 2007; Newnham et al., 2010).

Thirdly, as noted in the introduction, observations of the dispersal of ash plumes during historical and modern eruptions, such as the Eyjafjöll (Iceland) 2010 eruptions,imply that it is highly likely that ash from many of the Holocenerhyoliticeruptions from central TVZ volcanoes would have been delivered to and deposited in distal settings 300 km or more from New Zealand. To date, only Taupo, Waimihia, and now Whakatane, tephras have been

identified beyond this distance in the Holocene record. This sparseness in the distal marine records especially may be attributable to various causes including the following.

(1) Fallout from distal plumes can be scattered and patchy because of variable weather conditions (e.g., wind strength, local rainfall, regional synoptic conditions), and other factors, hence the likelihood of identifying a layer and recovering glass shards from any particular location is greatly reduced (e.g., Davies et al., 2010a; Pyne-O'Donnell, 2011).

(2) Reworking (erosion) and dispersal by ocean currents, slumping, or bioturbation in marine sediments may also constrain the probability of preservation and recovery in cores (e.g., Carter et al., 1995; Manville and Wilson, 2004b). Allan et al. (2008) noted from their study of three cores (A-C) at ODP Site 1123 that only ~20% of the tephras identified werefound in all three cores. They stated that thepreservation or otherwise of tephras in a core did not have any direct relationship to eruptive volume but instead was influenced by the vigorous nature of their deposition tothe ocean floor as vertical density currents.

(3)The sampling resolution of upper parts of marine cores may not have been adequate to detect very thin tephras, and it is possible in some cases thatthe uppermost sediments in marine cores (representing part of the Holocene) may not have been recovered in entirety (Carter et al., 2004).

(4) A major discovery from recent European and North Atlantic studies is that tephra records spanning the Late Quaternary are built entirely on the detection, recovery, and analysis of distal cryptotephras (e.g., Turney et al., 2006; Davies et al., 2010b). These are defined as glass-shard (and/or crystal) concentrations not visible to the naked eye as layers (Lowe, 2011). Some cryptotephra deposits have been recorded ~3000 km from source (e.g., Blockley et al., 2007). Although cryptotephra studies have been undertaken in New Zealand (e.g., Gehrels et al., 2006, 2008), no such studies have been carried out on marine cores taken

from the surrounding seas (Lowe, 2008). Consequently, distal ash-fall deposits preserved as (non-visible) cryptotephras in marine sediments would probably not have been sampled or studied because they were not recognised.

Therefore,cryptotephras, effectively glass-shard concentrations, are very likely to be present in many of the marine cores extracted from around New Zealand, and in the peat deposits on the Chatham Islands. The occurrence of thin Whakatane Tephra on Pitt Island shows that anything is possible given the right circumstances for dispersal, preservation, and recognition. Thus, new research to discover, extract, and identify (correlate) cryptotephras in deposits from the Holocene and earlier periods would be a valuable approach to enhance the chronostratigraphic record of the southwest Pacific region. It is well recognised that cryptotephra research, especially in the marine realm, is not without considerable difficulties (reviewed by Lowe, 2011), but nevertheless the potential for increasing the number of known tephra-based tie points, and hence isochrons, in the marine record and in peats on the Chatham Islands, must be large.

It would be extremely worthwhile to develop a programme to find additional tephras,most likely manifest as cryptotephras, in cores from these distal settings to enhance the tephrochronological frameworks that have been built in the wider New Zealand region already. The Chatham Islands are the easternmost occurrence of terrestrial Quaternary strata in New Zealand, and preserve a record of climate and environmental change in the remote southwest Pacific (Holt et al., 2010). Developing a much more detailed and comprehensive cryptotephrochronological framework, perhaps initially for the NZ-INTIMATE time-frame which includes the Holocene, will facilitate precise and accurate correlation between the Chatham Islands, mainland New Zealand, and the southwest Pacific Ocean.

5. **Conclusions**

TheWhakatane Tephra, erupted ca. 5500 cal. BP from the North Island's Okataina Volcanic Centre, has been identified as a ~5-mm-thick visible layer of very fine-ash-sized, highly siliceous (rhyolitic) glass shards within peat on Pitt Island. The first Holocene tephra to be recognised in the Chatham Islands, WT was identified using both ^{14}C dating and major-element analysis of glass shards by electron microprobe. The Pitt Island occurrence of WT, ~850 km from source, is the most distal Holocene tephra yet documented in the New Zealand region, eclipsing the previous maximum-distance record of 660 km for Taupo Tephra and 550 km for Waimihia Tephra.

The Pitt Island occurrence of WT extends its likely dispersal area markedly, by an order of magnitude, to possibly 300,000 km^2or more. A dispersal index (*D*) of a similar magnitude (approximately 10^5 km^2)implies that the eruption that generated the deposits was very powerful and had a high plinian eruption column that may have exceeded ~30 km in height. It is likely that sustained strong winds blew the ash plume southeastwards to enable its deposition on Pitt Island. Although the resultant deposit is very thin, such fine-grained ash nevertheless would represent a significant respiratory hazard to the inhabitants of the Chatham Islands if future eruptives from North Island were blown as far as the islands.

The presenceof WT on Pitt Island also highlights the potential for discovering cryptotephras both in the peats and lakes on the Chatham Islands and in the sediments of the southwest Pacific Ocean. Such cryptotephra studies, widely undertaken in the Northern Hemisphere, can be problematic in the marine environment especially (e.g., Davies et al., 2010b). But the successful recovery and identification of glass-shard concentrations in distal marine sediments, and on the Chatham Islands, would significantly enhancetephrochronological frameworks in these areas, facilitating the precise correlation of

key palaeoenvironmental records (such as NZ-INTIMATE) from mainland New Zealand, the Chatham Islands, and the southwest Pacific Ocean.

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Captions to figures and table

Fig. 1. (A) Map of New Zealand and the Chatham Islands depicting positions of the Taupo Volcanic Zone (TVZ) and Haroharo Linear Vent Zone (HLVZ). (B) Map of the Chatham Islands. The star denotes the location of the exposure containing the WT at New Zealand Map Series 260 (scale 1: 50,000), Chatham Islands Sheet 2, grid reference 750187. (C) Distribution of Whakatane Tephra fall deposits, shown as isopachs in centimetres, in the New Zealand region. Bold dashed lines indicate measured occurrences (based mainly on Kobayashi et al., 2005); additional measurements are from offshore cores as marked including those of Carter et al. (2002) and Shane et al. (2006). Pale dashed lines are inferred occurrences. Outermost fan-shaped isopach (>0 cm) is speculative (see text). KP, Kopouatai bog; KO, Kaipo bog; LP, Lake Poukawa.

Fig. 2.Location of Whakatane Tephra (arrow) as a thin (~5 mm) discontinuous layer within shallow peat that overlies Tertiary volcanic materials. Lenses of Kawakawa/Oruanui tephra (ca. 27,100 cal. BP) at the base of the peat are outlined in white. Spade is ~ 1 m high.Photographed by RCW.

Fig. 3. Calibration of ^{14}C age Wk-28291 (sample of peat enclosing Whakatane Tephra on Pitt Island) using OxCal4 (Bronk Ramsey, 2010) and SHCal04 Southern Hemisphere atmospheric curve (McCormac et al., 2004).

Fig. 4 (A) Average K_2O vsCaO composition of glass shards from Whakatane Tephra (WT) on Pitt Is. compared with that of glass of different magma types (T1, T2, or T3) of Kaharoa, Whakatane, and Rotoruatephras (data from Table 1). Error bars represent 1 standard deviation. Although compositionally similar to WT, neither Kaharoa nor Rotorua (magma type T2) can be correlatives of WT because the ^{14}C age obtained for WT on Pitt Island excludes them from consideration.

(B) K_2O vsCaO compositions of individual glass shards from WT on Pitt Is. compared with the compositional fields of glasses pertaining to the three batches of magma of the Whakatane eruptive episode: M = Makatiti vent eruptives, H = Haroharo vent eruptives, P = Pararoa vent eruptives. Compositional fields as presented by Shane et al. (2008, p. 47).

Table 1.

Major-element analyses of glass shards (via EMPA) from Whakatane Tephra on Pitt Island, and from the Whakatane, Kaharoa, and Rotoruatephras from proximal or reference locations on mainland New Zealand[a].

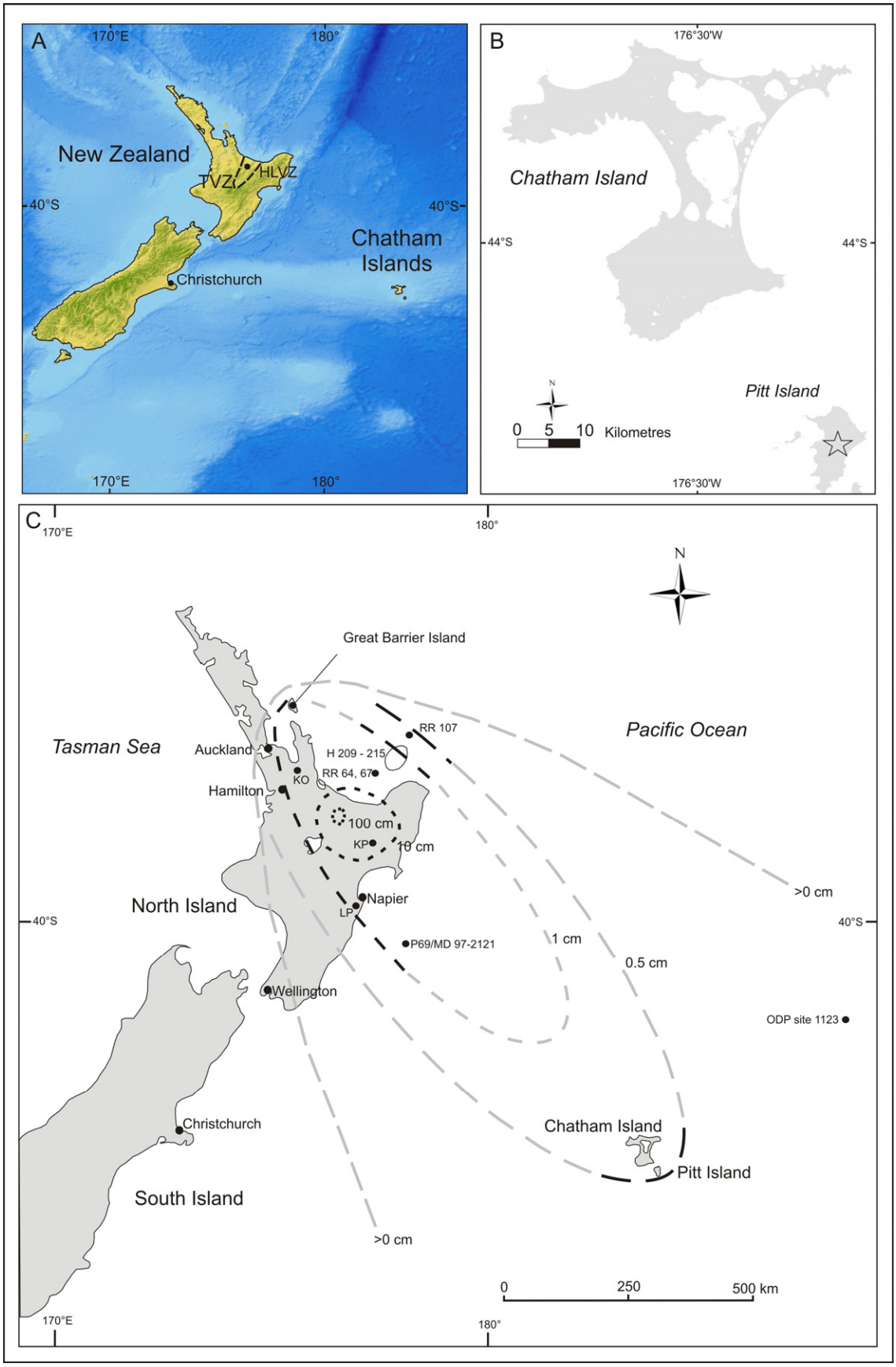
Footnotes

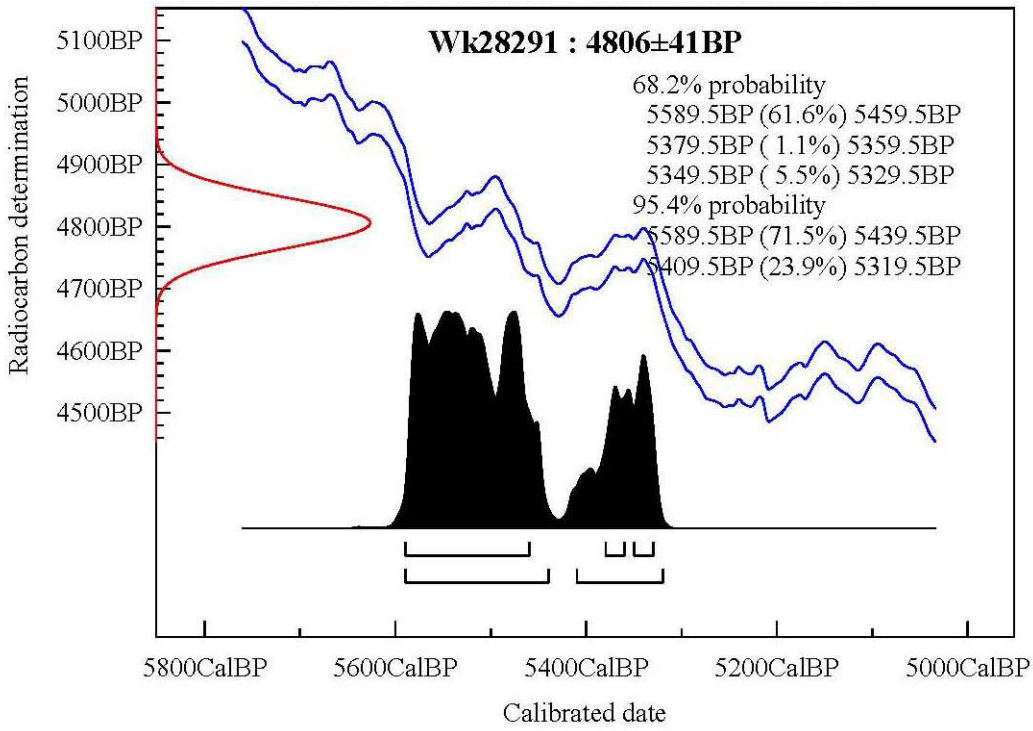
[a]Analyses recalculated to 100% on a volatile-free basis and expressed as a mean and standard deviation (in parentheses) in wt%. Total Fe expressed as FeO. Water calculated by difference from original analytical total and 100%. n = number of shards analysed.

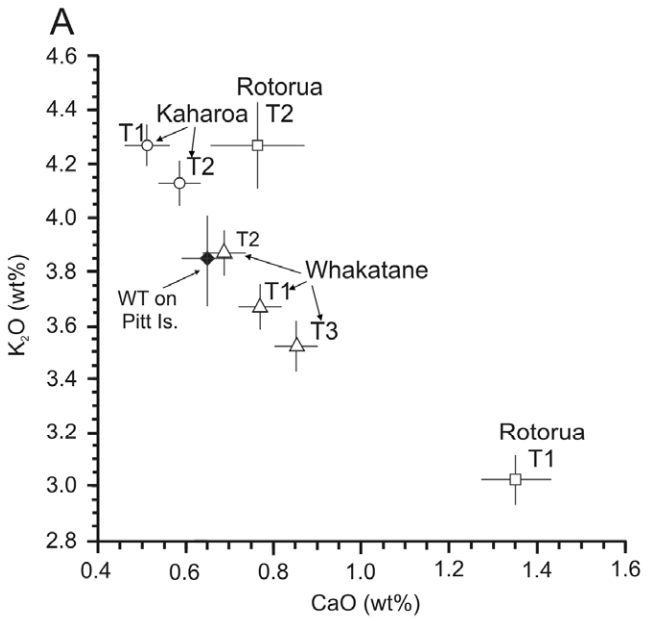
*Denotes Whakatane magma batches as defined by Kobayashi et al. (2005).

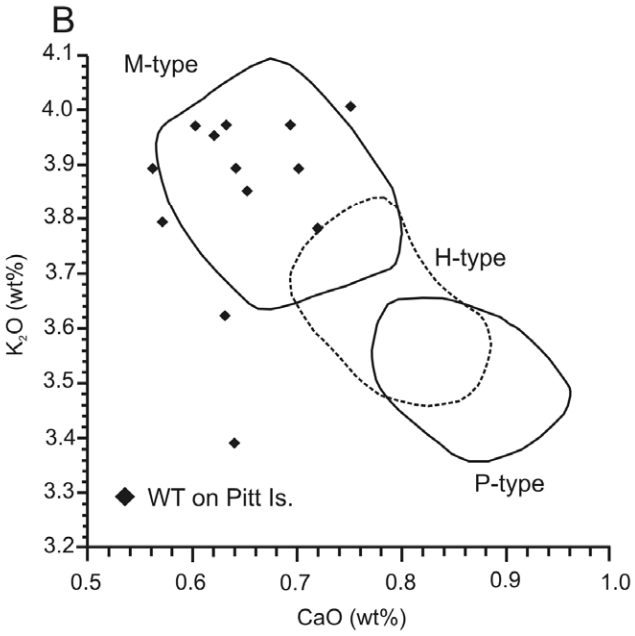
[◊]Denotes magma batch/eruption phase nomenclature of Lowe et al. (2008). Data from Kobayashi et al. (2005, p. 485) and Smith et al. (2005, p. 386), as published in Lowe et al. (2008, p. 105).

	Whakatane	Whakatane (proximal)			Kaharoa		Rotorua	
	(Pitt Island)	H*	M*	P*	T1◊	T2◊	T1◊	T2◊
		T1◊	T2◊	T3◊				
SiO_2	77.84 (0.19)	77.84 (0.20)	77.83 (0.23)	77.83 (0.27)	77.61 (0.19)	77.75 (0.18)	76.50 (0.29)	77.34 (0.20)
Al_2O_3	12.16 (0.12)	12.24 (0.11)	12.19 (0.10)	12.19 (0.07)	12.39 (0.11)	12.32 (0.07)	12.77 (0.23)	12.32 (0.06)
TiO_2	0.15 (0.05)	0.16 (0.07)	0.17 (0.07)	0.19 (0.07)	0.12 (0.06)	0.13 (0.05)	0.29 (0.08)	0.14 (0.12)
FeO	0.87 (0.06)	0.85 (0.09)	0.82 (0.09)	0.88 (0.15)	0.79 (0.07)	0.82 (0.07)	1.29 (0.13)	0.87 (0.12)
MnO	0.06 (0.07)	0.07 (0.05)	0.07 (0.07)	0.07 (0.04)	0.08 (0.05)	0.07 (0.05)	0.07 (0.06)	0.09 (0.07)
MgO	0.08 (0.06)	0.09 (0.06)	0.09 (0.06)	0.12 (0.06)	0.05 (0.04)	0.05 (0.04)	0.23 (0.08)	0.08 (0.05)
CaO	0.65 (0.06)	0.77 (0.05)	0.69 (0.05)	0.85 (0.05)	0.51 (0.05)	0.58 (0.05)	1.35 (0.08)	0.76 (0.11)
Na_2O	4.11 (0.15)	4.22 (0.13)	4.12 (0.15)	4.17 (0.12)	4.04 (0.12)	4.01 (0.13)	4.33 (0.12)	4.03 (0.11)
K_2O	3.85 (0.17)	3.67 (0.08)	3.87 (0.08)	3.52 (0.09)	4.26 (0.08)	4.13 (0.05)	3.02 (0.09)	4.26 (0.16)
Cl	0.25 (0.03)	0.16 (0.04)	0.17 (0.04)	0.15 (0.04)	0.15 (0.03)	0.15 (0.03)	0.15 (0.13)	0.15 (0.03)
H_2O	6.44 (0.51)	2.94 (1.48)	3.99 (1.71)	2.43 (0.73)	4.93 (1.80)	1.83 (0.50)	5.74 (1.65)	4.82 (1.52)
n	14	98	53	19	84	30	55	34


A
170°E
180°
New Zealand
TVZ
HLVZ
40°S
Chatham
Islands
Christchurch
170°E
180°
B
176°30'W
Chatham Island
44°S
44°S
N
0 5 10 Kilometres
Pitt Island
176°30'W
C
170°E
180°
N
Great Barrier Island
Tasman Sea
Auckland
RR 107
Pacific Ocean
H 209 - 215
RR 64, 67
KO
Hamilton
100 cm
KP
10 cm
>0 cm
Napier
North Island
LP
40°S
40°S
P69/MD 97-2121
1 cm
0.5 cm
Wellington
ODP site 1123
Christchurch
Chatham Island
Pitt Island
South Island
>0 cm
0 250 500 km
170°E
180°




A
Rotorua
Kaharoa
T1
T2
T2
T2
Whakatane
WT on
Pitt Is.
T1
T3
Rotorua
T1
K2O (wt%)
CaO (wt%)
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
0.4
0.6
0.8
1.0
1.2
1.4
1.6


B
M-type
H-type
P-type
WT on Pitt Is.
K2O (wt%)
CaO (wt%)
4.1
4.0
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
0.5
0.6
0.7
0.8
0.9
1.0