

Pyroclastic stratigraphy and eruption dynamics of the 21.9 ka Okareka and 17.6 ka Rerewhakaaitu eruption episodes from Tarawera Volcano, Okataina Volcanic Centre, New Zealand

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Abstract The 21.9 ka Okareka and 17.6 ka Rerewhakaaitu rhyolite eruption episodes began the construction of Tarawera Volcano in the Okataina Volcanic Centre, Taupo Volcanic Zone. Examination of the proximal and medial stratigraphy of these moderate-size (c. 5 km³ magma) but poorly exposed pyroclastic deposits has increased understanding of their eruption and dispersal processes. The Okareka Tephra consists of at least nine units (A - I), with unit A basaltic scoria at the base, overlain by the rhyolitic units B-I. Unit C is the largest individual plinian fall deposit (c. 0.4 km³), dispersed from an eruption column that reached c. 19 km height in the presence of strong cross winds. The other pyroclastic units record a variety of phreatomagmatic, sub-plinian, and small ignimbrite eruptions, which were followed by extrusion of voluminous lava flows.

The Rerewhakaaitu Tephra consists of 15 rhyolitic fall units A-N. An initial short plinian phase dispersed lapilli-fall unit A, mostly to ENE, from columns c.15 km in height. Units B-D have high ash contents, indicating phreatomagmatic eruptions with varying water-magma ratios, and were widely dispersed, with lobes to the northeast and southeast. Units E-J were deposited from 20-25 km high plinian eruption columns into strong cross winds that dispersed tephra to the southeast. The E-J package contains the largest tephra volume of the episode (1.18 km³) and is thought to dominate the deposits widely dispersed in Pacific Ocean sediments to the east of New Zealand. Rerewhakaaitu pyroclastic deposits are interbedded with, and underlie, voluminous lavas.

Keywords eruption episode; Tarawera; rhyolite; tephra; stratigraphy; dispersal; grainsizes; components; column dynamics; duration

INTRODUCTION

Tarawera Volcanic Complex is located in Haroharo Caldera, within Okataina Volcanic Centre (OVC) in Taupo Volcanic Zone (TVZ; Fig. 1 inset). Tarawera is one of two large intracaldera volcanic complexes active within the OVC during the last 25 k.y. (all dates are cal. yr BP) – the other being the Haroharo Volcanic Complex (Fig. 1). In the past 25 k.y., c. 80 km³ of magma has been erupted (as lavas and pyroclastics) from the OVC (Nairn 2002).

Tarawera Volcanic Complex consists of pyroclastics and lavas erupted during four rhyolite episodes and one basalt episode (Table 1). Basalt magma is a minor but significant component of volcanism at Tarawera; the most recent eruption in AD1886 produced only basalt magma (Table 1) from multiple vents defining a 17 km long northeast-trending fissure across the volcano (Cole 1970b; Nairn & Cole 1981). Basalt magma was also intimately associated with the c. 0.7 ka (Kaharoa) rhyolite episode (Leonard et al. 2002, Nairn et al.

2004), and the rhyolite-dominated 21.9 ka (Okareka) episode (Nairn 1992), but no basaltic component has been found in the 13.8 ka (Waiohau) rhyolite eruptives (Speed 2001; Speed et al. 2002).

The 21.9 ka Okareka and 17.6 ka Rerewhakaaitu eruption episodes are the two oldest recognised from Tarawera Volcano. Both episodes produced plinian fall deposits found throughout the central North Island (Vucetich & Pullar 1964; Pullar 1973), in cores from the Pacific Ocean to the east (Kohn & Glasby 1978; Carter et al. 1995; Newnham et al. 2003), and Auckland City to the northwest (Shane & Hoverd 2002). The Okareka eruption episode occurred near the peak of the last glaciation, whilst the Rerewhakaaitu fall deposits have been recognised as an important marker for the last glacial termination in New Zealand (Newnham et al. 2003).

Both the Okareka and Rerewhakaaitu episodes erupted high-silica rhyolite magma ($\text{SiO}_2 = 75\text{-}77$ wt%) as pyroclastics and lavas. Basalt magma erupted at the start of the Okareka episode forms a scoria deposit at the base of the tephra sequence. Hypersthene-hornblende rhyolite lava (Cole 1970c; Beggs 2002) was erupted at the end of the Okareka episode (Nairn 1992) to form the Ridge and Hawea lava flows (Fig. 1; Table 1). Biotite-hornblende rhyolite lavas of Rotomahana Dome (Fig. 1) were extruded at the start of the Rerewhakaaitu episode before the main pyroclastic eruptions, and the episode was terminated by the extrusion of hornblende-hypersthene (Western Dome) and dominantly hypersthene rhyolite magmas of Southern Dome and Te Puha lava (Cole 1970c; Nairn 2002). Mingling of the biotite-hornblende and hypersthene rhyolite magmas is observed in both Rotomahana Dome and Southern Dome, indicating these magmas were in close proximity before and at the time of eruption (Cole 1970b; Beggs 2002; Darragh 2004). The magmatic processes of the Okareka and

Rerewhakaaitu eruption episodes are to be described elsewhere (our work in progress). Here we present the stratigraphy and eruption dynamics of the Okareka and Rerewhakaaitu episodes to further detail the history and evolution of Tarawera Volcano, and to provide a stratigraphic basis for detailed studies of the magmatic processes that drove these episodes.

METHODS

Outcrops of Okareka and Rerewhakaaitu pyroclastic deposits have been examined and measured at 12 and 19 sites, respectively, around Tarawera. Younger eruptives and lakes cover Okareka deposits in the proximal area (see below), and the Rerewhakaaitu proximal deposits are rarely exposed, so that field correlation of individual eruptive units is difficult. The upper layers of both tephra are commonly truncated by erosion.

Units within each eruptive sequence have been defined in the field by distinct grain size and component characteristics, representing different eruption/deposition processes. Results from electron microprobe analyses of Okareka samples (our work in progress) have been used to confirm and modify some unit correlations originally presented in Darragh (2004). Data on the Okareka deposits is also included from Nairn (1992) for some sites not exposed during this study. Isopach and isopleth maps have been produced for selected units from each episode, and tephra volume calculations made using the method of Pyle (1989). Eruption column heights and wind velocities have been calculated using the method of Carey & Sparks (1986). The field data have been combined with grain size and component analyses to elucidate the eruption processes of both episodes. Grainsize analyses on bulk tephra samples were conducted following the methods of Folk (1968) and Walker (1981). Fine ash fractions

from samples with significant <0.063 mm contents were analysed by a Coulter LS130 laser-sizer at the IGNS Wairakei Research Centre. Grainsize terminology follows that set out by Cas & Wright (1988). Grainsize fractions were separated into component populations following the methods of Walker (1981) and Cas & Wright (1988).

OKAREKA ERUPTION EPISODE

Background and terminology

The “uppermost pinkish brown beds” of Vucetich & Pullar (1964) were later named “Okareka Ash” by Vucetich & Pullar (1969), who suggested a source at either “Mt Tarawera or Haroharo volcanic massifs” based on their limited isopach data. “Okareka Ash” at Lake Rotoiti was radiocarbon dated at 20,700 ¹⁴C yr BP (Vucetich & Pullar 1969) but the dated deposit was later identified as a pyroclastic surge erupted from the Haroharo complex during the preceding (25 ka) Te Rere eruption episode (Nairn 1989). Nairn (1992) described the Okareka Tephra deposits and their associated lavas in more detail, and confirmed a Tarawera source. A radiocarbon age of 18,420±149 ¹⁴C yr BP (Sandiford et al. 2002) has since been obtained for Okareka Tephra at Auckland, equivalent to a calibrated age of c. 21,900 cal. yr BP.

The original type section of the “Okareka Ash” (Vucetich & Pullar 1969) was at “the deep trench conveying the siphon pipe from Lake Okareka to Lake Tarawera” at U16/062305¹ (16 km northwest of the inferred source). Nairn (1992) considered the 117 cm of Okareka Tephra at this section to be overthickened due to downslope movement. Here we propose a newly

¹ All grid references in this paper refer to the NZMS 260 Topographic map series. See Nairn (1992) for a correction applied to the erroneous grid reference given in Vucetich and Pullar (1969) for this location.

exposed reference section for the Okareka Tephra, on Puhipuhi Hill at V16/256299 (Fig. 2), about 10 km northeast of the inferred source.

The Okareka Tephra is underlain by a paleosol developed in tephric loess overlying eruptives of the 25 ka Te Rere episode, and is overlain by tephric loess beneath the 17.6 ka Rerewhakaaitu Tephra. Okareka Tephra is identified in medial sections by the presence of basaltic scoria at the base of the sequence, and by the ferromagnesian mineral assemblage of the rhyolite pumice. There are two types of Okareka pumice: (1) crystal-poor with hypersthene + minor hornblende and biotite; and (2) crystal-rich with abundant hornblende + biotite. Pumice glass compositions vary through the Okareka eruption sequence (our work in progress), and “fingerprint” some of the eruptive units. No proximal Okareka pyroclastic deposits have been examined, as their vents are buried beneath the younger Kanakana - Ridge Dome area (Fig. 1) (Nairn 1992). The inferred Okareka episode vent locations are 8 km from the closest known exposures of Okareka pyroclastic deposits; closer deposits are buried by the Hawea and Ridge lavas extruded at the end of the Okareka episode, and by younger eruptives from Tarawera.

Unit A

Unit A is the earliest known eruptive of the Okareka episode and is a distinctive, black, well-sorted medium ash – lapilli fall deposit, c. 1-15 cm thick in medial sections (Fig. 2, 3, 4), dominated by basaltic scoria (60-70 wt%). The coarsest and thickest known exposures of Unit A occur along Savage Rd at V16/287265 and V16/274230 (sites 9 and 11 on Fig. 4), where it is c. 10-15 cm thick (though overthickened due to downslope movement at V16/287265). This distribution reflects proximity to a vent area inferred at Kanakana-Ridge Dome (Nairn 1992). Contacts with the underlying paleosol and overlying units are sharp but slightly

irregular. Lack of a paleosol or erosional surface between the basaltic scoria and overlying rhyolitic tephra implies continuity of eruption of the basaltic scoria and rhyolite. Scattered scoria clasts and grey pumices found at the base of the Okareka deposits in more distal sections (e.g., Bonisch Rd (V16/318196) and Pokairoa Rd (V16/403169)), sites 5 and 6 on Fig. 4, represent traces of Unit A.

Unit A also contains mingled basalt-pumice clasts (where cream-coloured pumice coats basaltic scoria), and 'grey' pumices, which are a result of more thorough basalt-rhyolite interaction giving rise to mixed (dacitic) compositions (Fig. 5) (Nairn 1992; Darragh 2004). Scoria clasts are characteristically coated with fine rhyolitic ash, which has been fused to the surface. Some rhyolitic pumice occurs in unit A and accessory (lithic) rhyolite, glass/obsidian and free crystals are also present (Fig. 5). Unit A has a relatively small elliptical dispersal area (Fig. 6) with a dispersal axis directed to the ENE. The unit has not been found to the west of Tarawera.

Unit B

Unit B marks the beginning of the rhyolitic phase of the Okareka episode and is thickest (13 cm) at McKee Rd 1 (V16/323254), and at Savage Rd 1 (Fig. 4; V16/274230) where the 24 cm ash thickness includes 1-2 cm layers of coarse ash and lapilli. Lapilli bands within the ash are also coarsest at this location, with pumices reaching 4 cm diameter and lithics between 1 and 2.5 cm. Similar successions occur in other sections where the typical Unit B layer has ash at top and bottom, enclosing lapilli layers.

Unit B was only sampled at Puhipuhi Hill (V16/256299; Fig. 2, 4, 5) where it has a high fine (<0.125 mm) ash content, is poorly sorted, and has a slight bimodal distribution. These

characteristics may indicate a phreatomagmatic origin, in sharp contrast to the underlying well-sorted unit A, and the overlying generally coarser unit C (Fig. 4, 5). Unit B is dominantly composed of crystal-poor pumice but also contains minor lithic rhyolite and glass/obsidian (Fig. 5), and rare basaltic scoria clasts, grey (mixed) pumices and mingled basalt-rhyolite clasts. Unit B displays a roughly subcircular medial fall dispersal pattern (Fig. 6). Some ash with Unit B glass chemistry has been found in cores of distal Okareka Tephra from Onepoto and Pukaki craters in Auckland (Fig. 1).

Unit C

Unit C is the coarsest fall deposit of the Okareka episode (Fig. 2, 4, 5) and is a creamy-grey, coarse ash-lapilli unit with thickest sections at Puhipuhi Hill (V16/256299; 61 cm thick; Fig. 2) and Savage Rd 1 (V16/287265; 50 cm thick; Fig. 4). Unit C commonly exhibits a slightly irregular lower contact with unit B (due to coarse ash-lapilli impacting onto finer ash), and a sharp planar contact with overlying units. Unit C is generally well sorted but contains minor ash layers up to 1 cm thick (Fig. 2, 5). One of these ash layers, sampled at Puhipuhi Hill, displays a low median diameter and poor sorting (Fig. 5). This ash may be co-ignimbrite ash from intra-plinian pyroclastic flows, or could result from brief phreatomagmatic or rain-flush activity. Most Unit C samples are pumice-rich (crystal-poor type), with generally minor amounts of lithic rhyolite lava clasts that dominate over glass/obsidian clasts (Fig. 5).

Unit C has a larger dispersal area and greater thickness than unit B (Fig. 6), and a coarser overall grain size in outcrop, suggesting it results from the most explosive and sustained plinian phase of the Okareka episode. Glass compositions of the Okareka Tephra found in cores from Onepoto and Pukaki craters suggest that Unit C is a major component of the distal tephra that reached Auckland (Fig. 1). The coarsest unit C deposits found are in the ENE sector at Puhipuhi Hill, Savage Rd 1 (V16/287265) and McKee Rd 1 (V16/323254) (Fig. 2, 4,

6) (Darragh 2004²), but no similar medial exposures are available to the northwest of Tarawera, where the overall dispersal pattern appears directed (Fig. 6). This dispersal pattern suggests a moderately high eruption column into a southeast wind.

Units D, E, F

These finely laminated fall units are well defined and thickest at the Puhipuhi Hill and Savage Rd 1 sections (Fig. 4, 5), but they become indistinguishable at most other sections around the volcano, where they are grouped as the “DEF” package (Fig. 4). Their textures and lithologies suggest these beds may either result from phreatomagmatic explosions or be co-ignimbrite ashfalls associated with now buried proximal pyroclastic flows. The overall dispersal of the D, E and F units indicates their eruption over a short duration into a southeasterly wind. These units also appear to have reached Auckland as similar glass compositions are found as a minor component of Okareka Tephra in the Onepoto core.

Unit D: Unit D is c. 12 cm thick at Puhipuhi Hill (V16/256299; Fig. 2, 5), and is a greyish-tan, poorly sorted, coarse to fine ashfall deposit, with faint laminations revealing subtle changes in grain size. It displays a sharp, planar contact on unit C below and has sharp contacts with overlying unit E. Samples from the Puhipuhi Hill section (Fig. 5) and the McKee Rd 1 section (V16/323254) (Darragh 2004), have an extended fine-tailed size distribution and are poorly sorted, with pumice and glass/obsidian the dominant constituents.

The sharp contact between the unit C and D deposits, and their strongly contrasting grain sizes, suggests that an abrupt change in eruption dynamics occurred at the transition between the C and D eruptions. A gradual decrease in emission rate would produce a smoothly upward-fining transition (Walker 1981; Jurado-Chichay & Walker 2001), but the sudden

² Full grainsize and componentry data are available from the first author.

change in the deposits was likely produced by a change in vent conditions (such as introduction of external water), or collapse of the plinian eruption column dispersing unit C, as the magma supply was throttled. Although we cannot discount a phreatomagmatic origin, we interpret unit D at Puhipuhi Hill (Fig. 4) as a co-ignimbrite ash (Watanabe et al. 1999), associated with proximal pyroclastic flows produced by sudden column collapse and confined to valleys at lower elevations.

Unit E: Unit E is a 3.5 cm band of dark grey, well sorted medium-coarse ashfall at Puhipuhi Hill (Fig. 2, 4, 5). It has a sharp lower contact with unit D, but grades into overlying units. It consists dominantly of glass/obsidian, with less pumice and lithic rhyolite clasts. Some unit E pumice has higher crystal content (typical of crystal-rich pumice) and contains biotite. These characteristics suggest that fall unit E was produced by a brief explosive` phase through less vesicular, slightly chilled magma in the conduit.

Unit F: Unit F is 25 cm thick at Puhipuhi Hill (Fig. 2, 4) and consists of pinkish beige-brown coloured, fine-medium, alternating laminated ashes. It is also well developed at Savage Rd 1 (Fig. 4). Unit F usually has a sharp basal contact but tends to grade into overlying units or be interbedded with them. Samples from Puhipuhi Hill and McKee Rd 1 sections (Fig. 4; Darragh 2004) are dominated by pumice and glass/obsidian, have an extended fine-tailed distribution and are poorly sorted, suggesting fragmentation was influenced by water/magma interaction.

Unit G

Unit G is defined from Puhipuhi Hill (Fig. 2), although it is thickest (c.70 cm) at the Savage Rd 3 section (site 11 on Fig. 4). Unit G is a creamy-grey, well sorted, medium-coarse ash-dominated fall unit with scattered lapilli and weak bedding (Fig. 5). At McKee Rd 1, the grain

size distribution correlates more closely with the lower two-thirds of unit G at Puhipuhi Hill (where it is coarser), suggesting that the lower portion of unit G was dispersed to the east (Darragh 2004). Pumice is the major constituent, with a significant amount of glass/obsidian (Fig. 5). Pumices are dominantly crystal-poor with rare biotite-bearing types. Unit G deposits are interpreted as fall deposits from a dominantly dry magmatic (sub-plinian?) explosive phase.

Unit H

Unit H is a distinctive, silver-grey, massive, well-sorted, medium to fine ash fall deposit about 20 cm thick at Puhipuhi Hill (Fig. 2). Elsewhere it is well defined only to the southeast at Savage Rd 3, Okahu Rd, and Bonisch Rd (Fig. 4), where it is between 15 and 20 cm thick. It tends to have sharp contacts with underlying units but gradational upper contacts with unit I, usually defined by a sharp change in colour to orange-brown. The upper contact is locally gullied at Puhipuhi Hill and Bonisch Rd (Fig. 4). Unit H beds are dominantly composed of pumice, glass shards and free crystals, and are the finest grained of the analysed Okareka eruptives (Fig. 5), with 98.1 wt% of the Puhipuhi Hill sample finer than 0.25 mm. Unit H is also tentatively correlated to other locations, at Rotoiti Rd (to north) and Red Tank Rd (to west - Fig. 4), where grainsize data show similarly high <0.25 mm contents (Darragh 2004). Unit H is 19 cm thick at Bonisch Rd (Fig. 4), showing that this unit is well dispersed, though erosion of the upper Okareka beds at many locations and lack of exposure prevent further correlations.

Unit I

Unit I is the uppermost Okareka episode tephra preserved at Puhipuhi Hill, where it is a distinctive orange-brown, rather massive ash (plus scattered lapilli), overlain by tephric loess and the 17.6 ka Rerewhakaaitu Tephra (Fig. 2, 5). Unit I is also tentatively correlated to

Savage Rd 3, Okahu Rd and Bonisch Rd (Fig. 4), where it is better preserved as a 15 cm thick medium to coarse ash fall bed. Unit I was only sampled at the Puhipuhi Hill section (Fig. 2, 5), where it is poorly sorted but has a lower <0.25 mm content than underlying unit H. It is pumice-rich (crystal-poor type) with minor glass/obsidian. Its limited outcrop and common reworking prevent inferences as to likely eruptive origin.

Units J, K, L

The sections at Okahu Rd and Bonisch Rd expose this package of later-erupted Okareka units not seen in other sectors (Fig. 4), but a truncated upper contact beneath tephric loess means that an unknown thickness of the Okareka eruption sequence is missing even from here.

Units J, K, L are c.1 m in total thickness at Bonisch Rd, where they comprise finely laminated ash beds that include very weakly cross bedded ignimbrite flows, and co-ignimbrite ashes.

The very limited available exposure prevents more detailed interpretation of these units, which seem to have been strongly confined into the southeast sector (Fig. 6).

REREWHAKAAITU ERUPTION EPISODE

Background and terminology

Rerewhakaaitu Tephra conformably overlies tephric loess formed on 21.9 ka Okareka Tephra, and is overlain by 15.7 ka Rotorua Tephra (Nairn 2002). Vucetich & Pullar (1964) first identified the distal tephra fall deposits as “Rerewhakaaitu Ash”, and indicated a Tarawera source. Cole (1966, 1970a,b,c) confirmed the Rerewhakaaitu Ash as having been erupted from Tarawera and described the associated lavas. Nairn (1989) described proximal pyroclastics of the episode and termed these the “Rerewhakaaitu Pyroclastics”, recognising them as lateral equivalents of Rerewhakaaitu Ash, and erupted from vents in the Rerewhakaaitu tuff cone - Southern Dome area (Fig. 1). An error-weighted mean radiocarbon

age of $14,700 \pm 95$ ^{14}C yr BP (n=4) for the Rerewhakaaitu Ash is equivalent to a calibrated age of c. 17,600 cal. yr BP (Newnham et al. 2003).

The original type section for the “Rerewhakaaitu Ash” (Vucetich & Pullar 1964) was located at V16/140150 near Lake Rerewhakaaitu, 8 km south of the Tarawera vent area. A second reference locality for thick proximal pyroclastic flow deposits of the episode (Nairn 1989) is in gullies at the Rerewhakaaitu tuff cone just southeast of the vent (Fig. 1; V16/167229-V16/168233). In this paper, we propose a new medial-distal reference section (Rw 1 - Fig. 7, 8) at V16/238270 (8 km northeast of the vent) for the Rerewhakaaitu Tephra fall deposits dispersed north of the volcano.

Rerewhakaaitu Tephra contains two pumice types: (1) crystal-poor (c. 3% modal) with hypersthene; and (2) crystal-rich (c. 19% modal) with abundant hornblende + biotite (Cole 1970a). Component analyses (Darragh 2004) reveal that both pumice types occur in all tephra units throughout the Rerewhakaaitu episode.

Unit A

At Rw1 (Fig. 7), unit A lies on tephric loess mantling the Hawea lava (Okareka episode), and is a distinctively speckled, well-sorted coarse ash to lapilli bed, 12-15 cm thick (Fig. 7, 8, 9). Similar thicknesses occur in sections at Savage Rd and Rerewhakaaitu Rd (Fig. 8, 10A), but the coarsest deposits are at Rw1, with pumices ranging up to 3.5 cm in diameter, and lithics c. 1 cm (Fig. 9). In sections farther to the east (downwind) and south, unit A is thinner and fines to medium-coarse ash (Fig. 8). Unit A is dominated by pumice (both crystal-poor and crystal-rich types), with high contents of (largely accessory) lithic rhyolite lava clasts (Fig. 9) reflecting vent wall erosion during the eruption. Some rare pumice clasts exhibit what appears

to be subtle mingling of mafic magma (basalt?) with rhyolite, and one hypocrySTALLINE basaltic clast was found at Rw1.

At the Rerewhakaaitu Rd section (site 2 on Fig. 8), 8 km south of the vent, a 15 cm thick coarse ash-lapilli bed here correlated with unit A is conformably underlain by 20 cm of medium-coarse ash, which rests on tephric loess (Fig. 8). This basal medium-coarse ash is not found at other sites farther east (e.g., Okahu Rd, site 6 on Fig. 8), and it contains abundant crystal-rich pumice that distinguishes it from the overlying unit A (Darragh 2004). The basal ash deposit at Rerewhakaaitu Rd appears to record an initial phase of unit A that was only dispersed to the south. It may be associated with the eruption of Rotomahana Dome, which was probably extruded at the start of the episode (Nairn 2002).

Unit A isopachs are poorly constrained, but indicate a subelliptical, northeasterly dispersal pattern (Fig. 11). The coarse and well-sorted nature of unit A and its field characteristics, suggest it was deposited from a relatively short lived plinian eruption column.

Units B-D

Units B-D reflect a sharp change in eruption dynamics from those of unit A, as they consist of a package of stratified ash beds with generally smaller median diameter and poorer sorting (Fig. 9) than unit A. At the Rw1, Savage Rd 1, and McKee Rd 1 sections (Fig. 8), the package comprises two ash beds (units B and D) separated by a lapilli bed (unit C), and each of these units can be easily identified (e.g., Fig. 7, 10A). At other sections, the three units are interbedded or appear as a set of multiple lapilli and ash beds and cannot be separated (e.g., Fig. 10B).

At Rw1 (Fig. 7, 8, 9), unit B comprises 34.5 cm of tan-brown, poorly sorted ash beds, with some lenses of coarser ash and scattered lapilli; some of the finer ash beds pinch out laterally (over 1-2 m). Unit B lies sharply but irregularly on the lapilli of unit A, and has a similar upper contact with unit C, which consists of 6 cm of poorly sorted lapilli-ash (Fig. 7). Lapilli-sized pumice scattered in this unit are up to 8 cm diameter, with rhyolite lithics to 4 cm (Fig. 9). Unit C has sharp, irregular upper and lower contacts (because of the finer nature of the bounding beds against coarser lapilli). At Rw1, unit D is 50 cm of well-bedded fine-coarse brown ash with rare, laterally discontinuous lapilli bands (Fig. 7), and sharp upper and lower contacts. Units B and D are dominated by pumice (of both modal types) but are also reasonably lithic-rich, with high glass/obsidian and lithic rhyolite contents (Fig. 9) (Darragh 2004). These units are dispersed in two weakly developed lobes extending to the northeast and southeast (Fig. 11).

The stratified nature of the B-D units, their large <0.25 mm contents, poor sorting and lithic-rich component populations (e.g., Fig. 9) suggest these are fall beds resulting from phreatomagmatic eruptions. Unit C, which is coarsest and best developed at Rw1 (Fig. 9), may record a short period of less magma-water interaction, when fragmentation was dominantly magmatic. The multiple lapilli and ash beds found at this stratigraphic level at other locations (e.g., Okahu Rd, Ngamotu Rd and Pokairoa Rd; Fig. 8,10B) suggest there were fluctuating changes in water-magma ratios at the vent.

Units E-J

Unit E is a grey, moderately well sorted lapilli fall bed, thickest at Rw1 (17 cm; Fig. 7, 9), where it has a sharp planar lower contact on unit D and a sharp, irregular upper contact with unit F. Pumice lapilli range up to 5.5 cm diameter and lithics to 4.5 cm. Along Savage Rd,

unit E is 15-16 cm thick (Fig. 8, 10A). Unit F at Rw1 consists of c. 12 cm thick well-sorted fine-medium ashes with sharp planar internal bedding (Fig. 7). Here, and at Savage Rd 1 (Fig. 8, 10), unit F sits sharply and irregularly on unit E (mainly due to ash resting on lapilli) and has a sharp planar contact with overlying unit G. Unit G comprises 20 cm of poorly sorted, alternating fine, medium, and coarse ash fall beds plus scattered lapilli, with a sharp, planar upper contact (Fig. 7, 9). Unit H is a grey, well-sorted ash-lapilli bed, 13 cm thick at Rw1 (Fig. 7, 9), where it grades from basal ash up into coarse ash and lapilli, capped by thin interval of fine ash with a sharp, planar upper contact with unit I.

Unit I is a distinctive bed of silvery-grey, loose, very well sorted ash exhibiting subtle reverse grading and sharp planar upper and lower contacts. It is well defined at Rw1, where it is 11 cm thick (Fig. 7, 9), and at Savage Rd 1 where it is 9 cm thick (Fig. 8, 10A), but it cannot be identified at sections farther south and east. Unit J consists of an alternating sequence of fine, medium and coarse ash fall beds with scattered lapilli, 164 cm thick at Rw1 (Fig. 7, 9). At sections farther south the finer ash beds are thinner and less laterally continuous.

Units E-J are individually defined at the Rw1 reference section, but cannot be separated in most other locations, particularly to the south of the reference section (e.g., Fig. 10B). In this study, units E-J have been treated as a package between the finer ash of units D and K (Fig. 7, 8, 9, 10). The E-J units represent the bulk of the Rerewhakaaitu Tephra fall deposits, dispersed from plinian eruption columns. In the ENE dispersal sector (especially at Rw1, c. 8 km from the vents), the finer ash beds are thicker and suggest fluctuating eruption intensity, reflected by the sharp contacts of coarser material on top of finer (and vice versa), and some reverse grading (e.g., Fig. 7, 10A). At other sections to the east and southeast of vent, grainsize changes and characteristics are more subtle and consistent up-section, because the

fine ash beds are thinner or poorly represented in that sector, where the coarsest unit E-J beds are seen (e.g., Fig. 8, 10B) (Darragh 2004).

All unit E-J beds are pumice-dominated (both crystal-rich and crystal-poor types), with unit E lithics at Rw1 having a higher wall rock-derived rhyolite lava content than the glass/obsidian-dominated G-J beds (Fig. 9). In unit E-J beds to the south of Rw1, the lithic fraction contains more rhyolite lava than glass/obsidian (Darragh 2004).

Isopachs of units E-J define an elliptical shape with a southeasterly dispersal axis (Fig. 11), reflecting the thick deposits on Okahu, Bonisch, Ngamotu, and Pokairoa Roads (Fig. 8) and also near Murupara (at V17/324982 and V17/300979). The coherent southeasterly trend suggests that units E-J were erupted over a short duration while the same wind pattern was in effect, and that high eruption columns were maintained in the presence of strong winds.

Units K-N

Unit K consists of fine-grained, well-sorted, glass/obsidian dominated ash at Rw1 (where it is 11 cm thick), Savage Rd 2 (8 cm), McKee Rd (7 cm and 4.5 cm), and Ngamotu Rd (7 cm) (Fig. 7, 8). The ash of unit K is interpreted as representing a decline in eruption activity when there was a decreasing supply of gas-poor magma. Units L-N are defined and analysed from Rw1 (Fig. 9), and can be correlated to sections on McKee Rd 1 and 2, and Bonisch Rd (Fig. 8). At Rw1, units L-N have similar size and component characteristics to the unit J beds below (Fig. 9), and are interpreted as fall beds from an unstable column re-established after the break recorded by unit K. Units L-N are not well preserved or exposed around Tarawera, and they may be condensed into a single package in some sections, or be removed by erosion at others.

TEPHRA VOLUME CALCULATIONS AND ERUPTION COLUMN HEIGHTS

Methods

Non-consolidated tephra volumes were calculated (Darragh 2004) for Okareka fall units A, B, C, and the DEF and GHI packages, and for Rerewhakaaitu units A, B-D, and E-J (Table 2), using the method of Pyle (1989). This method assumes exponential thinning of tephra with distance from the vent. Plots of \ln thickness versus $\text{area}^{1/2}$ were produced (Fig. 12) for each of the isopach maps (Darragh 2004). In most cases, only two or three isopachs were available for estimation (due to the difficulty of identifying units in distal areas, and the lack of outcrop), so that only one straight-line segment could be defined for most plots of the individual fall units. Volumes were also estimated for the total Okareka and Rerewhakaaitu Tephra deposits, using the thickness of the whole deposit at each location. For these calculations, two line segments were defined for each episode deposit (Fig. 12) and a correction (Pyle 1995) applied to the data.

Eruption column heights were estimated for Okareka unit C and Rerewhakaaitu units A and E-J, based on isopleth maps of maximum lithic (M_L) sizes (Fig. 13), using the method of Carey & Sparks (1986). Densities of lithic clasts were calculated using the buoyancy method (Brown 1981), and modelling of plume characteristics was based on 1 cm lithics of 2000 kg/m^3 density for Okareka unit C and Rerewhakaaitu unit A (Table 3). Modelling using both 1 cm and 2 cm clasts of the same density was done for Rerewhakaaitu units E-J (Table 3). In calculating the column heights, only two or three isopleths (Fig. 13) were available for measuring the downwind and crosswind ranges.

Okareka Tephra

The unit A (basaltic) tephra volume of 0.02 km^3 (Table 2) is the best constrained calculation with a (V/V_{TOTAL} of 91%). Calculations for the tephra units B and C yield larger volumes, as

expected for plinian rhyolitic eruptions, and as demonstrated by their higher b_t values (Table 2). Both estimates are poorly constrained due to few available outcrops, but they show unit C to be the dominant plinian phase of the Okareka episode (Table 2). Eruption column height calculations (Table 3) (Carey & Sparks 1986; Darragh 2004) suggest that the maximum height of the columns dispersing unit C was c. 19 km, erupted into winds of 24 m/s which dispersed the tephra northwest to Auckland.

Rerewhakaaitu Tephra

Tephra volume calculations are better constrained for Rerewhakaaitu units (Table 2). Unit A volume is 0.07 km^3 ($V/V_{\text{TOTAL}} 74 \%$). Units B-D have a minimum volume of 0.28 km^3 in the Tarawera area (Table 2). The 1.18 km^3 volume of units E-J is well constrained (Table 2) and establishes this package as accounting for much of the total Rerewhakaaitu volume deposited in the study area. The unit A eruption column was c. 14-15 km high and dispersed by winds of c. 25 m/s (Table 3). Unit E-J columns were c. 20-25 km high and dispersed to the southeast by strong winds (20 to $>30 \text{ m/s}$) (Table 3, Fig. 11). Estimates were not made for units B-D due to their dominantly finer grain sizes, lack of maximum clast data for isopleth mapping, and variations in appearance in different sectors (e.g., Fig. 7, 8, 10).

TOTAL DEPOSIT CHARACTERISTICS

Okareka Tephra

Measurements of the Okareka Tephra original total thickness are limited by erosion of the upper part of the primary deposit, which occurred before preservation of the remaining tephra by accumulation of the overlying tephric loess. A weak paleosol developed in this loess before the post-eruption land surface was fixed by deposition of the Rerewhakaaitu Tephra. The total Okareka Tephra volume calculated here (11.9 km^3 ; Table 2) includes the post-Okareka loess, and may be a significant overestimate if the tephric loess thickness exceeds

that of the eroded primary tephra layers. Previous volume estimates for Okareka Tephra range from 4.8 km³ to 8 km³ (Pullar 1973; Froggatt & Lowe 1990). Benny et al. (1988) showed that reworking of other sources continued after the Okareka episode and that some post-Okareka loess is not derived from Okareka Tephra, thus inflating the volume estimate. Few outcrops of Okareka Tephra exist in proximal and medial areas, and it has only rarely been recognised in offshore cores (Fig. 11), so that its true extent is not well defined.

Rerewhakaaitu Tephra

Rerewhakaaitu Tephra stratigraphy is similar to the Okareka Tephra sequence in some sectors (e.g., ENE) in that it is generally well bedded, with many changes in grain size, reflecting varying eruption processes and intensities. However, some Rerewhakaaitu Tephra units, well defined to the northeast of Tarawera, become less distinctive to the southeast, where they have to be grouped into unit packages.

The Rerewhakaaitu Tephra contains relatively thin and/or fine-grained units in some near-source sections (Rw1, Rw2; Fig. 8), but exhibits thick and/or coarse packages in some more distant exposures (e.g., Bonisch Rd and Pokairoa Rd, Fig. 8). It also has a large offshore dispersal to the southeast (Fig. 11), with c. 2 cm thickness in cores taken from the Hikurangi Plateau (Carter et al. 1995; Newnham et al. 2003), whilst 0.3 cm of Rerewhakaaitu Tephra is found in the opposing (northwestern) sector at Auckland (Shane & Hoverd 2002) (Fig. 11).

We estimate a total tephra volume of c. 7.6 km³ (Table 2) by closing the 5 cm isopach.

Newnham et al. (2003) estimated the total volume of Rerewhakaaitu Tephra at 14 km³ (closing the 2 cm isopach).

The Pyle (1989) model predicts that 90% of the Rerewhakaaitu Tephra units E-J volume has been enclosed by the 25 cm isopach (Table 2, Fig. 11) though it would seem that these E-J

beds may also represent the bulk of the deposits widely dispersed offshore to the southeast. This is probably true because of the reasonably high columns attained by the E-J sequence and their eruption into high wind conditions (Table 3). Upper parts of the Rerewhakaaitu Tephra (units L-N) are poorly exposed and may be truncated by erosion, but may also have been erupted into a high wind regime dispersing them great distances to the southeast.

Probable episode durations

No evidence exists of any significant erosion or weathering interval between any pyroclastic units in either the Okareka or Rerewhakaaitu episodes, suggesting that the pyroclastic phases of both episodes occurred relatively continuously. Nairn et al. (2001) suggested possible durations of 10-40 days for intermittent plinian eruptions during the 0.7 ka Kaharoa episode from Tarawera, and we suggest that similar durations (i.e., weeks to months) are reasonable for eruption of the Okareka and Rerewhakaaitu Tephra.

The Hawea and Ridge lavas were interpreted by Nairn (1989, 1992) as the final phase of the Okareka episode. Froggatt & Lowe (1990) estimated the volume of Okareka lavas as 5 km³ and Rerewhakaaitu lavas as 2 km³. Nairn (2002) presented stratigraphic evidence for Rotomahana Dome being erupted at the start of the Rerewhakaaitu episode, with Southern Dome, Western Dome, and Te Puha lavas erupted towards the end of the episode. The extrusion of these voluminous (e.g., >1 km³) lavas after the pyroclastic phase of both episodes would have taken years, if rhyolite lava extrusion rates were of order 10 m³/s (Nairn et al., 2001). The duration of the Kaharoa episode has been estimated at c. 4 yr, with lavas extruded over a 2-3 yr period (Nairn et al., 2001); a similar duration is estimated for the Waiohau episode (Speed et al., 2002). We infer total durations of several years for both the Okareka and Rerewhakaaitu eruption episodes.

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Table 1 Stratigraphy and chronology of Tarawera Volcano (from Nairn 1989, 2002).

Episode and age (cal. yr BP)	Lavas	Pyroclastics
Tarawera AD 1886	Basalt dikes beneath AD 1886 craters	Tarawera Pyroclastics Rotomahana Pyroclastics Rotomahana Tephra
Kaharoa 0.7 ka	Ruawahia, Tarawera, Wahanga Domes Green Lake Plug Crater Dome	Kaharoa Pyroclastics Kaharoa Tephra (plinian)
Waiohau 13.8 ka	Kanakana Dome Pokohu lava flows Waikakareao lava flows Eastern Dome	Waiohau Pyroclastics Waiohau Tephra (plinian) Local pyroclastic deposits at Rotomahana
Rerewhakaaitu 17.6 ka	Southern Dome Te Puha lava flow Western Dome Rotomahana Dome	Rerewhakaaitu Pyroclastics (tuff cone) Rerewhakaaitu Tephra (plinian)
Okareka 21.9 ka	?Ridge Dome Ridge lava flow Haweia lava flow Patiti Island	Okareka Tephra (plinian) Scoria fall (sub-plinian)

Table 2 Parameters used for estimation of tephra volumes, calculated using the method of Pyle (1989, 1995). T_0 = extrapolated maximum thickness at vent. b_t = thickness half distance. - k = slope of log thickness vs. area^{1/2} plot. $A^{1/2}_{ip}$ = value at intersection of the two line segments (for the total deposit volumes only). V/V_{TOTAL} = fraction of total tephra volume contained within the last closed isopach. Ok = Okareka; Rw = Rerewhakaaitu. ¹ Near vent segment of total measurements; ² Distal segment of total measurements.

Unit	-k	b_t (km)	T_0 (m)	$A^{1/2}_{ip}$	Volume (km ³)	V/V_{TOTAL}
Ok A	-0.2582	1.515	0.585		0.02	0.91
Ok B	-0.0776	5.040	0.389		0.13	0.39
Ok C	-0.0679	5.759	0.809		0.35	0.62
Ok DEF	-0.0671	5.828	1.093		0.49	0.69
Ok GHI	-0.0612	6.390	1.601		0.86	0.76
Ok Total	-0.0733 ¹	5.335 ¹	4.18 ¹		-	-
	-0.0123 ²	31.794 ²		19.5	11.89	
Rw A	-0.1431	2.733	0.690		0.07	0.74
Rw B-D	-0.1459	2.680	2.935		0.28	0.75
Rw E-J	-0.1408	2.777	11.648		1.18	0.90
Rw Total	-0.1365 ¹	2.865 ¹	16.485 ¹		-	-
	-0.0187 ²	20.913 ²		20.5	7.57	-

Table 3 Estimated column heights and wind velocities for eruption columns of the Okareka and Rerewhakaaitu episodes.

Unit	Clast diameter (cm)	Maximum Downwind range (km)	Crosswind range (km)	Est. column height (km)	Est. wind velocity (m/s)
Ok C	1	17.5	6.5	19.2	24
Rw A	1	12.25	4.2	14.7	25
Rw E-J	1	23.25	10.25	25.0	21.5
Rw E-J	2	18.0	5.75	20.6	>30

Figure captions

Fig. 1 Map of Tarawera Volcanic Complex (Tarawera Volcano), showing distribution of lava domes, flows, and proximal pyroclastics (modified from Nairn 2002). *Inset*: Map showing location of the Okataina Volcanic Centre (OVC) and map area (box) in the Taupo Volcanic Zone (TVZ).

Fig. 2 Okareka Tephra at the medial reference section on Puhipuhi Hill at V16/256299. Units are defined in the text. Scale is 1 m in length, with 10 cm graduations.

Fig. 3 Medial exposure of Okareka Tephra at Okahu Rd (V16/248190; Ok4 on Fig. 4). Units are defined in the text. Rw is Rerewhakaaitu Tephra. Scale is 1 m in length, with 10 cm graduations.

Fig. 4 Correlation of Okareka Tephra units on transects around the volcano.

Fig. 5 Selected grainsize distribution and component histograms for sampled units from the Okareka reference section at Puhipuhi Hill (V16/256299). Units are identified on the stratigraphic column and in the histograms. Inman parameters of sorting (σ_ϕ) and median diameter (Md_ϕ) and are plotted to the right of the stratigraphic column. Sorting is based on classification of Cas & Wright (1988); 0-1 very well sorted; 1-2 well sorted; 2-4 poorly sorted; >4 very poorly sorted. Median diameter phi (ϕ) sizes are; -2 (4 mm), 0 (1 mm), 2 (0.25 mm), 4 (0.063 mm). Components of the <0.25 mm (2 ϕ) size fractions in all samples were not analysed. See Darragh (2004) for more data.

Fig. 6 Isopach maps of Okareka units, total medial Okareka Tephra, and distal dispersal. All thicknesses are in centimetres. Additional distal data are from Vucetich & Pullar (1969); Pullar (1973); Stewart & Neall (1984); Lowe (1988); Nairn (1992); Donoghue et al. (1995); Nelson et al. (2000) and Shane & Hoverd (2002).

Fig. 7 Rerewhakaaitu Tephra at reference section Rw1 at V16/238270. Units as defined in text. Geologist is c. 1.8 m in height.

Fig. 8 Correlation of Rerewhakaaitu Tephra units; **(A)** around the volcano, and **(B)** downwind of the volcano. Refer to Fig. 4 for key to symbols.

Fig. 9 Selected grainsize distribution and component histograms of Rerewhakaaitu Tephra units at reference section Rw1 (V16/238270). Units are defined in text beside the stratigraphic column and in the histograms. Inman parameters of sorting (σ_ϕ) and median diameter (Md_ϕ) and are plotted to right of the stratigraphic column. Sorting based on classification of Cas & Wright (1988); 0-1 very well sorted; 1-2 well sorted; 2-4 poorly sorted; >4 very poorly sorted. Median diameter phi (ϕ) sizes are; -2 (4 mm), 0 (1 mm), 2 (0.25 mm), 4 (0.063 mm). Components of the <0.25 mm (2 ϕ) size fractions in all samples were not analysed. See Darragh (2004) for more data.

Fig. 10 Medial and distal exposures of Rerewhakaaitu Tephra at **(A)** Savage Rd 1 (V16/287265; Rw13 on Fig. 8) and **(B)** Pokairoa Rd (V16/403169; Rw18 on Fig. 8). Scale is 1 m in length, with 10 cm graduations.

Fig. 11 Isopach maps of Rerewhakaaitu units A, B-D, E-J, total thickness of medial Rerewhakaaitu Tephra, and distal dispersal. All thicknesses in cm. Additional distal data for total thickness map from Vucetich & Pullar (1964); Pullar (1973); Kohn & Glasby (1978); Stewart & Neall (1984); Lowe (1988); Carter et al. (1995); Donoghue et al. (1995); Lowther (1997); Crosby (1998); Lowe et al. (1999); Eden et al. (2001); Shane & Hoverd (2002).

Fig. 12 Area^{1/2} vs log thickness plots for: **A**) Units A, B and C of the Okareka Tephra and total Okareka tephra thickness; and **B**) Units A, B-D and E-J of the Rerewhakaaitu Tephra and total Rerewhakaaitu tephra thickness. Two segments are defined for each total tephra thickness.

Fig. 13 Isopleth maps of maximum lithic grain sizes (M_L) for Okareka unit C and Rerewhakaaitu units A and E-J. Measurements are in centimetres.
