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Revision of the age and stratigraphic relationships of Hinemaiaia Tephra and Whakatane Ash, North Island, New Zealand, using distal occurrences in organic deposits

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Abstract The stratigraphic and chronologic relationships of Hinemaiaia Tephra and Whakatane Ash are examined using distal tephras preserved in organic-rich deposits at five sites in eastern and northern North Island, New Zealand. A c. 10 mm thick, unnamed white rhyolitic ash layer described at two of the sites (Tiniroto and Poukawa), and previously of disputed stratigraphic significance, also occurs at the other three sites (Kaipo, Rotomanuka, and Okoroire) as a primary airfall tephra. The tephra is derived from the Taupo Volcanic Centre and is correlated with Hinemaiaia Tephra (definition of Froggatt) using similarity of stratigraphic position, composition (ferromagnesian mineralogy and glass chemistry), and radiocarbon age. It stratigraphically overlies Whakatane Ash. The tephra underlying Whakatane Ash, and previously identified as Hinemaiaia Ash (definition of Vucetich & Pullar), is probably Motutere Tephra.

Hinemaiaia Tephra has a mean age of (old T½) c. 4500 years, Whakatane Ash c. 4800 years. New ^{14}C dates, obtained on peat or gyttja adjacent to these tephras, are (old T½, years B.P.): 4220 ± 60 (NZ3160A), 4490 ± 70 (Wk541) (above Hinemaiaia Tephra); 4470 ± 70 (Wk542) (below Hinemaiaia Tephra); 4800 ± 50 (NZ3161A), 4490 ± 60 (Wk496), 4530 ± 60 (Wk497), 4260 ± 140 (Wk662) (below Hinemaiaia Tephra and above Whakatane Ash); 5210 ± 80 (NZ3162A), 4860 ± 70 (Wk501), 4850 ± 80 (Wk660) (below Whakatane Ash).

Based on the distal occurrences described here, the Hinemaiaia Tephra has a much more widespread distribution than previously demonstrated, and may have been emplaced by a very powerful "above average" plinian eruption.

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Keywords Hinemaiaia Tephra Formation; Hinemaiaia Ash Formation; Whakatane Ash Formation; pyroclastics; Holocene; stratigraphy; tephrostratigraphy; organic matter; C-14; isopach maps; glasses; chemistry; electron probes; explosive eruptions

INTRODUCTION

Late Quaternary tephras erupted from rhyolitic and andesitic sources in the Taupo Volcanic Zone (Fig. 1), and from Mt Egmont and Mayor Island, cover large areas of the North Island (e.g., Pullar et al. 1973; Howorth et al. 1981). Following early reconnaissance mapping of these deposits, chiefly for soil survey purposes (e.g., Grange 1931), many studies in the past 20 years have concentrated on the stratigraphy, age, and distribution of the tephras near their source areas (e.g., Healy 1964; Vucetich & Pullar 1964; Howorth 1975). During this period it has been found that tephra deposits proximal to a particular source commonly contain interbedded distal deposits from outside centres, and a more complex tephrostratigraphy than originally described has ensued (e.g., Topping & Kohn 1973; Vucetich & Pullar 1973; Stewart et al. 1977; Howorth & Topping 1979). Largely because of their thinness in relation to the locally derived deposits, the distal tephras can be difficult to trace or identify with certainty in the field, especially where affected by weathering or soil-forming processes. Similar problems are evident in distal sequences consisting wholly of thinly bedded tephras (e.g., Vucetich & Pullar 1969; Pullar & Birrell 1973; Hodder & Wilson 1976).

Two approaches have been applied to circumvent this problem. The first has involved detailed laboratory-based tephra "fingerprinting" methods (e.g., Kohn 1970, 1979; Topping & Kohn 1973; Hogg & McCraw 1983); the second has been the utilisation of sections or sediment cores of muddy or organic-rich deposits within which discrete tephra layers are separated and preserved (e.g., Topping & Kohn 1973; Kohn & Glasby 1978; Howorth et al. 1980; Lowe et al. 1980). These latter studies have begun to provide not only an improved chronology for many of the tephras (through radi-

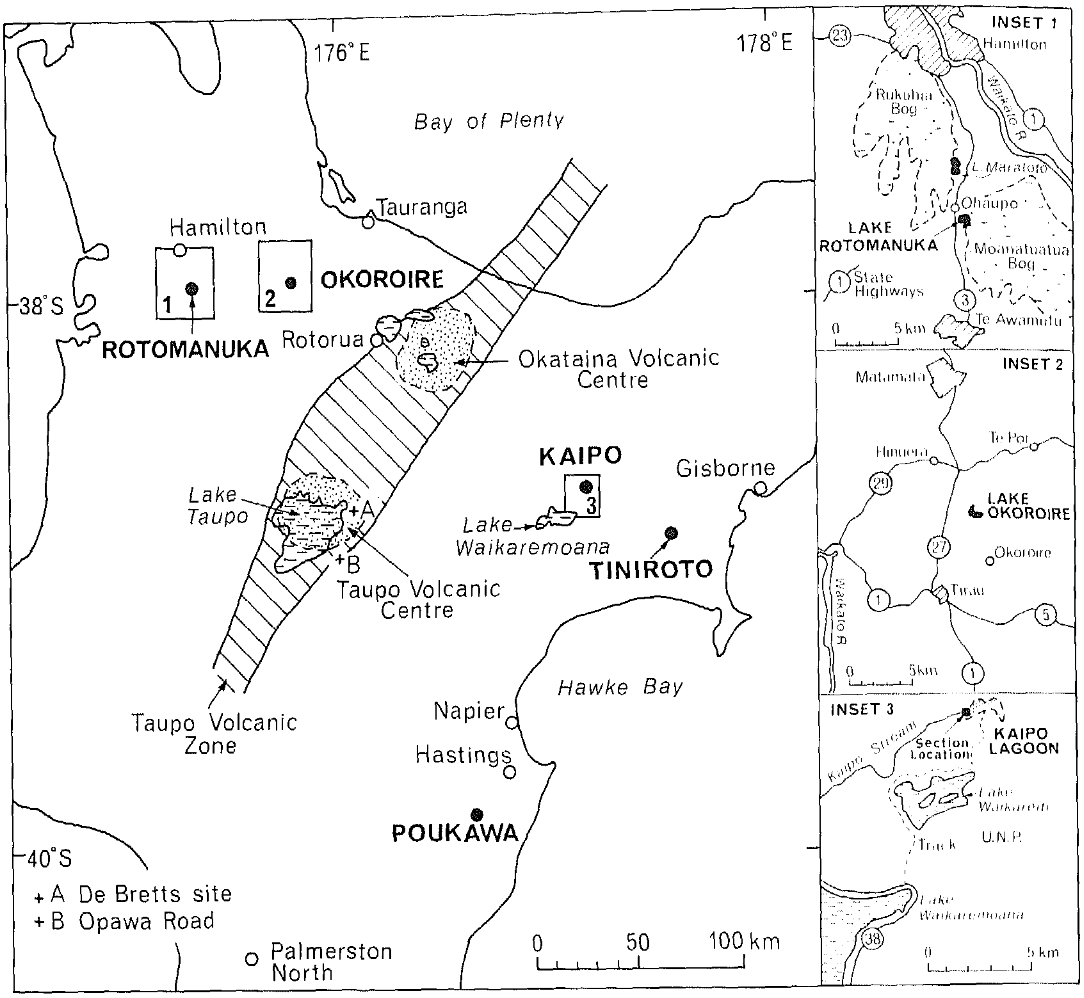


Fig. 1 Location map of the Poukawa, Tiniroto, Kaipo, Rotomanuka, and Okoroire sites in the North Island showing their distant positions peripheral to the Okataina and Taupo Volcanic Centres. The boundaries of the Taupo Volcanic Zone and volcanic centres are from Cole & Nairn (1975). Insets show detailed locations of Kaipo Lagoon, Lake Rotomanuka, and Lake Okoroire. U.N.P. = Urewera National Park.

ocarbon dating of the intervening organic sediments) but also a clearer record of the stratigraphic relationships of interbedded tephras derived from different volcanic centres.

In this paper, distal tephras contained within peat and organic lake sediments (gyttja) are investigated to determine the stratigraphic and chronologic relationships of two Holocene tephras, the Taupo-derived Hinemaiaia Tephra (defined by Froggatt 1981a) and the Okataina-derived Whakatane Ash (defined by Vucetich & Pullar 1964). From studies in the Taupo area, Vucetich & Pullar (1973) defined Hinemaiaia Ash and considered it to be stratigraphically overlain by Whakatane Ash. Froggatt (1981a), in redefining Hinemaiaia Ash as Hinemaiaia Tephra, essentially followed the stratigraphy of Vucetich & Pullar (1973) which, until now, has been unquestioned. However, recent examination of the tephras in peat and gyttja deposits at Kaipo, Rotomanuka, and Okoroire, in eastern and northern North Island (Fig. 1), identified a thin rhyolitic ash layer which, with regard to its characteristics and stratigraphic position, could not be correlated with any known proximal eruptive. Moreover, such an "unnamed rhyolitic tephra" had previously been found in a similar stratigraphic position in organic sediments at Tiniroto and Poukawa (Fig. 1), although its stratigraphic significance at these sites was disputed (Howorth & Ross 1981; Kohn et al. 1981). It is shown here that the unnamed rhyolitic tephra found at all of these distal sites is the same eruptive unit and that it is a correlative of Hinemaiaia Tephra. That Whakatane Ash stratigraphically underlies Hinemaiaia Tephra at the distal sites has meant revision of the stratigraphic and chronologic relationships previously described by Vucetich & Pullar (1973) and Froggatt (1981a) for these tephras.

The revision includes 10 previously unpublished ^{14}C dates on the Hinemaiaia Tephra and the Whakatane Ash. Electron microprobe analyses of glass shards from the distal correlative of Hinemaiaia Tephra and from Whakatane Ash are given, and implications of the possible widespread distribution of Hinemaiaia Tephra in the North Island are examined.

STRATIGRAPHY AND CHRONOLOGY OF THE HINEMAIAIA AND ASSOCIATED TEPHRAS IN THE TAUPO AREA

In a revision of earlier work by Baumgart (1954) and Healy (1964), Vucetich & Pullar (1973) defined the Hinemaiaia Ash Formation (symbol Hm) at the De Bretts Hotel type section near Taupo (Fig. 1). The Hinemaiaia Ash, established as originating from the Taupo Volcanic Centre, was defined as lying conformably between the Whakatane Ash Formation and the Rotoma Ash Formation (these last two tephras being derived from the Okataina Volcanic Centre; Fig. 1). It was dated at c. 6200 years old by correlation with a tephra at Tiniroto that had ^{14}C dates of 6390 $\pm$ 120 (NZ1137)* and 6190 $\pm$ 70 (NZ1247) years B.P. (Pullar & Heine 1971; Vucetich & Pullar 1973). Vucetich & Pullar (1973) noted that both Whakatane and Rotoma tephras were infrequently exposed around Taupo and were difficult to distinguish with certainty. In many sections, Hinemaiaia Ash was sandwiched within a multiple paleosol with a blotchy appearance. Of the tephras derived from Taupo, Hinemaiaia Ash lies between Waimihia Formation (above) and Opepe Tephra Formation (below).

Froggatt (1981a) redefined the Hinemaiaia Ash as the Hinemaiaia Tephra Formation (Hm) at a new type site in Opawa Road in Lake Taupo State Forest (Fig. 1). Recognising the difficulty of identifying the Whakatane and Rotoma tephras as discrete units in the Taupo area (Whakatane Ash could not be found at Opawa Road), he purposely defined Hinemaiaia Tephra in relation to locally mappable Taupo-source tephras only. It was thus defined as the rhyolitic tephra lying conformably between the Waimihia Lapilli Formation and the paleosol capping the Motutere Tephra Formation. The Motutere Tephra, a Taupo-derived tephra first recognised and described by Froggatt (1981a), and similarly defined without reference to Okataina-source tephras, lies below the Hinemaiaia Tephra and overlies the paleosol on Opepe Tephra. Froggatt (1981a) considered that both Hinemaiaia Tephra and Motutere Tephra were wholly airfall deposits in the type area. The volume of the Hinemaiaia Tephra is c. 3 km^3 (Froggatt 1982a). New ^{14}C dates of 4650 $\pm$ 80 years B.P. (NZ4574) for the Hinemaiaia Tephra, and 5370 $\pm$ 90 years B.P. (NZ4846) for the Motutere Tephra, both determined on charcoal found in the type area, were published by Froggatt (1981a).

Other dates of possible relevance to these tephras were collated in a summary diagram by Froggatt (1981a, p. 103). Whakatane Ash, with ages ranging from 4600 to 5180 years, is shown between Waimihia Lapilli and Hinemaiaia Tephra. This stratigraphy, based on Vucetich & Pullar (1973), tacitly implies that Hinemaiaia Tephra, like Hinemaiaia Ash, underlies Whakatane Ash. However, Froggatt's (1981a) definition does not preclude the possibility of Hinemaiaia Tephra occurring stratigraphically above Whakatane Ash. Motutere Tephra, significantly older than Hinemaiaia Tephra by about 700 radiocarbon years, therefore probably underlies Whakatane Ash (Froggatt 1981a), as discussed later.

Thus, at the time of publication of Froggatt's (1981a) paper, there was effectively no new information regarding the stratigraphic relationship of the Hinemaiaia and Whakatane tephras beyond that of Vucetich & Pullar (1973). Moreover, Froggatt's caution regarding the identification of Whakatane Ash in the Taupo area indicates that Vucetich & Pullar's (1973) stratigraphy with respect to this tephra must be viewed as uncertain. In comparing the ages, and associated errors, of the Hinemaiaia and Whakatane tephras, it is evident that the solitary ^{14}C date on the Hinemaiaia Tephra (Froggatt 1981a) is indistinguishable from most of those available for Whakatane Ash (a few are several hundred years older: Grant-Taylor & Rafter 1971; Howorth et al. 1980). Hence, in the absence of a definitive section containing both tephras, a chronologic separation based on the published dates is unjustifiable.

*NZ = New Zealand Radiocarbon Dating Laboratory number. These and other ^{14}C ages discussed in the text are all conventional ages based on the old half-life of 5568 years. See also Table 2.

STRATIGRAPHY OF DISTAL TEPHRAS IN ORGANIC DEPOSITS IN EASTERN AND NORTHERN NORTH ISLAND

Previous studies at Tiniroto and Poukawa (Fig. 1) have reported the occurrence of an uncorrelated rhyolitic ash layer between the Waimihia and Whakatane tephras, but its existence and stratigraphic significance have been disputed, and its identification is problematical. However, since this previous work was published, three further sections or sediment cores containing airfall tephras intercalated with organic deposits have been investigated — at Kaipo Lagoon (Urewera National Park) and at Lake Rotomanuka and Lake Okoroire (both in the Waikato region). In these sections, which have a more comprehensive tephrostratigraphy than at Tiniroto and Poukawa, a rhyolitic tephra also occurs between the Waimihia and Whakatane tephras or within the general age range they span. The nature, stratigraphic position, and age of this tephra, and those immediately adjacent to it, are specifically examined to establish its origin and possible correlation with Hinemaiaia Tephra.

Tephrostratigraphy

Tiniroto

The sequence of tephras preserved within muddy lacustrine sediments has been variably interpreted largely because of unreliable radiocarbon dating (Vucetich & Pullar 1964, 1973; Pullar & Heine 1971; Howorth & Ross 1981; Kohn et al. 1981). Most studies have noted the presence of a thin (c. 10–25 mm) rhyolitic tephra, or "ashy horizon", lying between the Waimihia and Whakatane tephras (labelled Un in column 2, Fig. 2) that has been assigned several names. Kohn et al. (1981) called it an "unnamed rhyolitic tephra" that "records an eruption from the Taupo Volcanic Zone which has not been previously recognised on the east coast of the North Island" (p. 65). This conclusion was based on its orthopyroxene-rich ferromagnesian mineralogy, its stratigraphic position above Whakatane Ash (considered to be aged between 4680 ± 100 years B.P. (NZ1358) and 5180 ± 80 years B.P. (NZ1066)), and the apparent lack of any known rhyolitic eruption in this time period (between Waimihia and Whakatane tephras). The tephra below Whakatane Ash at Tiniroto was correlated with Hinemaiaia Ash from its stratigraphic position and mineralogy, and its age was estimated at between 4680 ± 100 years B.P. (NZ1358) and 6345 ± 130 years B.P. (NZ427).

In contrast, Howorth & Ross (1981) dismissed the "ashy horizon" as being of no stratigraphic importance due to its occurrence in one core only and within sediments described as badly slumped. The tephra below Whakatane Ash was identified as Hinemaiaia Ash (column 1, Fig. 2) and assigned an age of c. 5500 years old (based on correlation with a tephra in a similar stratigraphic position at Poukawa: Howorth et al. 1980).

Poukawa

The stratigraphy of the Holocene tephras preserved in peats and lake sediments at Poukawa has been described by Pullar (1970), Howorth et al. (1980), and B. P. Kohn, V. E. Neall & R. B. Stewart (unpublished manuscript, V. E. Neall pers comm.). The last workers, as at Tiniroto, recorded at Poukawa a thin (c. 10 mm) "unnamed rhyolitic white coarse ash" lying below Waimihia Lapilli and just above Whakatane Ash (column 4, Fig. 2). It was ^{14}C dated from peat above at 4220 ± 60 years B.P. (NZ3160) and below at 4800 ± 50 years B.P. (NZ3161). The tephra below Whakatane Ash was identified as Hinemaiaia Ash.

Howorth et al. (1980) did not record any tephra layer between Waimihia and Whakatane tephras at Poukawa. Whakatane Ash was dated between 4600 ± 90 (NZ3948) and 4640 ± 90 (NZ3949) years B.P.; the tephra below was identified as Hinemaiaia Ash with ^{14}C dates of 5680 ± 130 (NZ3950) years B.P. (above) and 5370 ± 90 (NZ3951) years B.P. (below) (column 3, Fig. 2). However, Froggatt (1981a) concluded that this tephra was probably a correlative of Motutere Tephra (dated at 5370 ± 90 years B.P. (NZ4846) near the source), and this correlation presumably also applies to the tephra identified as Hinemaiaia Ash by Kohn, Neall & Stewart at Poukawa.

Kaipo Lagoon

Kaipo Lagoon is a montane peat bog located near Lake Waikareiti, north of Lake Waikaremoana. Kaipo Stream, draining the bog, has exposed a 3 m section at its western end (Fig. 1) that shows interbedded tephras and peats overlying material dated at about 11 000 years old (Lowe & Hogg 1986). At a depth of about 1 m is a 5–10 mm layer of white pumiceous ash (labelled HmT in Fig. 2). It underlies Waimihia Lapilli and overlies, within 2–3 cm, Whakatane Ash. It has a modal ferromagnesian mineralogy (2–4ϕ fraction) of 95% orthopyroxene and 5% clinopyroxene (based on point count). This composition indicates a Taupo source (Froggatt 1981b). The Whakatane Ash was identified by its characteristic cummingtonite-dominated (65%) ferromagnesian mineralogy (Kohn & Glasby 1978; Howorth et al. 1980) and its age (Fig. 2). The difference in mineralogy indicates that the white ash layer cannot be a disturbed fragment derived from the Whakatane Ash. The Waimihia Lapilli was identified by its field characteristics, its

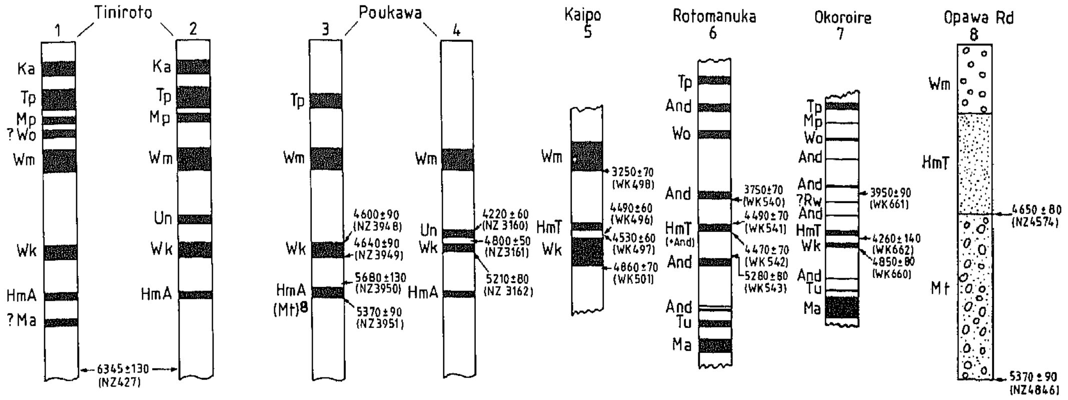


Fig. 2 Schematic stratigraphic columns of tephras and ^{14}C dates at Tiniroto, Poukawa, Kaipo, Rotomanuka, Okoroire, and Opawa Road (Taupo) sites; ages are in years B.P. (old T½) (see also Table 2). The "unnamed rhyolitic tephra" is labelled either Un or HmT (see below).
Ka, Kaharoa Ash; Tp, Taupo Pumice; Mp, Mapara Tephra; Wo, Whakaipo Tephra; Wm, Waimihia Lapilli; ?Rw, possibly Rotokawau Ash; Un, unnamed rhyolitic tephra (correlated with HmT in this study); HmT, Hinemaiaia Tephra (of Froggatt 1981a); Wk, Whakatane Ash; HmA, Hinemaiaia Ash (of Vucetich & Pullar 1973) (probably correlates with Mt); Mt, Motutere Tephra; Tu, Tuhua Tephra; Ma, Mamaku Ash; And, uncorrelated andesitic tephra. Sources, and specific locations of new sites (Fig. 1), are: 1, Howorth & Ross (1981); 2, Kohn et al. (1981); 3, Howorth et al. (1980); 4, B.P. Kohn, V. E. Neall & R. B. Stewart (V. E. Neall pers. comm.), section located on northern margin of Lake Poukawa at NZMS 260 map grid reference V22/281522; 5, this study, section located at W18/740720; 6, this study, core site at S15/136615; 7, this study, core site at T15/555611; 8, Froggatt (1981a).

orthopyroxene-dominated ferromagnesian mineralogy (100%), and a carbon date of 3250 ± 70 years B.P. (Wk498)* (Fig. 2; Lowe & Hogg 1986). It is most unlikely that the white ash has derived from reworking of the overlying Waimihia Lapilli, being separated from it by a generally uniform 25–30 cm thickness of peat.

The white ash layer can be traced as a discrete bed c. 20 m along the exposure of peat. The ^{14}C dates of 4490 ± 60 years B.P. (Wk496) and 4530 ± 60 years B.P. (Wk497) were obtained on samples c. 2 cm thick taken from beneath the tephra at two sites c. 10 m apart on the section face. These dates apply equally to the white ash and to Whakatane Ash because the samples spanned the entire layer of peat between the tephras. The date of 4860 ± 70 years B.P. (Wk501) here gives a maximum age of the Whakatane Ash (Fig. 2). The dates from Kaipo are consistent with minimal mixing in the section, further indicating that the white ash layer has not been reworked (Lowe & Hogg 1986).

Lake Rotomanuka

Lake Rotomanuka is a shallow (< 8 m) lake located adjacent to the Moanatuatua bog near Ohaupo about 15 km south of Hamilton (Fig. 1). It was formed when a valley was dammed by alluvium (Hinuera Formation) at least 17 000 years ago (Green & Lowe 1985). A series of sediment cores was collected using a modified Livingstone piston corer. The cores, up to 3.5 m long, contain numerous thin, discrete tephra layers, derived from various volcanic sources, interbedded with gyttja. Such tephras have been described and correlated previously for nearby Lake Maratoto by Lowe et al. (1980) and Green & Lowe (1985). By virtue of its greater sedimentation rate, its less peaty character, and perhaps its slightly more southerly, nearer source location, Lake Rotomanuka contains a clearer and more detailed tephrostratigraphic record than Lake Maratoto, particularly in the upper one-third of the sediment column.

The tephrostratigraphy of part of a core from Lake Rotomanuka is shown in Fig. 2. A thin (3–5 mm) white, fine ash layer (HmT in Fig. 2) occurs at a depth of c. 0.5 m below Taupo Pumice. It is straddled by andesitic tephras, probably from a Mt Egmont source (D. J. Lowe in prep. "Stratigraphy, chronology, and correlation of late Quaternary distal rhyolitic and andesitic tephras interbedded with organic sediments in the Waikato region, North Island, New Zealand"), which are dated at 3750 ± 70 years B.P. (Wk540) and 5280 ± 80 years B.P. (Wk543) (Fig. 2); their ferromagnesian mineral assemblages are dominated by clinopyroxene

*Wk = University of Waikato Radiocarbon Dating Laboratory number (Hogg 1982).

(augite) and hornblende in approximately equal amounts. The white fine ash is found in five other cores taken from the lake. In some of these it is intermixed with a contemporary, slightly coarser ash derived from Mt Egmont additional to those noted above. Neither Waimihia nor Whakatane tephras were identified as megascopic layers, although the latter may be sparsely present as microscopic "dust" associated with the underlying andesitic tephra. Because of the thinness (ranging from only c. 1-5 mm) of the white ash, insufficient ferromagnesian minerals could be extracted from it for an accurate point count, but both orthopyroxene and clinopyroxene were present. Dates of 4490 ± 70 years B.P. (Wk541) and 4470 ± 70 years B.P. (Wk542) were obtained from 1-2 cm thick slices of gyttja taken from above and below the tephra, respectively (Fig. 2). A thin, white ash layer of similar age (as estimated from sedimentation rates) and stratigraphic position is known to occur in at least four other lakes (Rotokauri, Ngaroto, D, and Mangahia) in the Hamilton area.

Lake Okoroire

Lake Okoroire, located about 5 km north of Tirau (Fig. 1), is a shallow peaty lake similar to Lake Rotomanuka in origin and character. Three cores, up to 3 m long, were taken, as at Rotomanuka, revealing a similar tephrostratigraphy (Fig. 2). An unnamed white fine ash layer (HmT in Fig. 2) occurs c. 0.3 m below Taupo Pumice, and is underlain by Whakatane Ash and overlain by an Egmont-derived tephra, each within c. 1 cm of it in the core. The white fine ash layer, 8-10 mm thick, was found in each core taken. It has a ferromagnesian mineralogy (2-4ϕ fraction) of 87% orthopyroxene with 13% clinopyroxene. The Whakatane Ash was identified by cummingtonite (81%). The andesitic tephra overlying the white ash contains clinopyroxene and hornblende in approximately equal amounts in the ferromagnesian mineral assemblage.

A 1 cm thick slice of gyttja between the white fine ash and the Whakatane Ash was dated at 4260 ± 140 years B.P. (Wk662); a 2 cm thick slice below Whakatane Ash was dated at 4850 ± 80 years B.P. (Wk660) (Fig. 2). The andesitic tephra immediately above the white ash layer is aged c. 4100 years based on the date 3950 ± 90 years B.P. (Wk661) obtained 3 cm above it in the core (Fig. 2).

Glass chemistry

Glass shards were extracted from three samples of the uncorrelated white ash from the Kaipo and Rotomanuka sites and analysed for nine major elements using an electron microprobe (Table 1). The results show that each of the tephra layers sampled is homogeneous, as indicated by the generally low standard deviations (cf. Froggatt & Gosson 1982, p. 10); sample 1 shards have the smallest, and sample 3 shards the greatest, variance. The compositions are remarkably similar to one another (Fig. 3A), as demonstrated by the similarity coefficients of the sample-pair histograms (Fig. 3B) whose values, near 1.0, lie within the range that typically indicates an origin from a single emplacement unit (Borchardt et al. 1972; Sarna-Wojcicki et al. 1984; Davis 1985). The small coefficient of variation (CV) values (< 6.0) similarly indicate a close chemical match (Borchardt et al. 1971; Froggatt 1983).

The analyses confirm that the white ash is rhyolitic in composition, and favour an origin in the Taupo Volcanic Centre (Table 1, Fig. 4). All Taupo-derived tephras of Holocene age apparently have similar major element compositions (exemplified by Motutere Tephra in Table 1), and most appear chemically indistinguishable from one another on this basis (Froggatt 1981b, 1982b; see also glass analyses in Ewart 1963 and Froggatt 1983). However, they are quite distinct from many of the Okataina-derived tephras (e.g., Whakatane Ash, Table 1), as illustrated in Fig. 4 for CaO and FeO (see also glass analyses in Cole & Nairn 1975 and Kohn 1979). (The Holocene Taupo-derived tephras also contain more Al_2O_3, TiO_2, and MgO, but less K_2O, than the Okataina-derived tephras.)

CORRELATION OF THE UNNAMED RHYOLITIC TEPHRA WITH HINEMAIAIA TEPHRA AND STRATIGRAPHIC IMPLICATIONS

The occurrence of the unnamed rhyolitic tephra at Kaipo, Okoroire, and Rotomanuka as a distinct stratigraphic unit supports the arguments for its existence as a genuine primary tephra at Tiniroto and Poukawa. Moreover, in considering all sites, the tephra manifestly has many features in common.

(1) It is white with comparable grain size (fine to coarse ash) and thickness (av. c. 10 mm) compatible with a distal location.

(2) It has an orthopyroxene-dominated ferromagnesian mineralogy (demonstrated for four sites) indicative of a Taupo Volcanic Centre source.

(3) It has a radiocarbon age of between c. 4200 and c. 4800 years (av. c. 4500 years: Table 2).

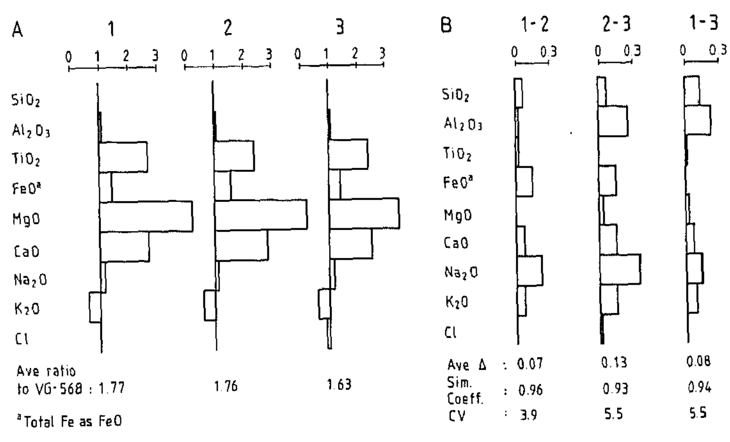
(4) It occupies a similar stratigraphic position (Fig. 2): at Kaipo, Poukawa, and Tiniroto the tephra occurs stratigraphically below the Waimihia Lapilli and just above Whaka-

Table 1 Chemical analyses of glass from the unnamed white ash, Motutere Tephra, and Whakatane Ash, as determined by electron microprobe*. The analyses are normalised to 100% loss free.

	White ash					
	1	2	3	4	5	6
SiO_2	76.90 (0.23)	76.97 (0.57)	77.04 (0.77)	76.97 (0.52)	77.01 (0.22)	78.41 (0.24)
Al_2O_3	12.99 (0.10)	13.01 (0.27)	12.75 (0.38)	12.92 (0.28)	13.18 (0.11)	12.41 (0.15)
TiO_2	0.19 (0.03)	0.17 (0.04)	0.17 (0.02)	0.18 (0.03)	0.16 (0.01)	0.12 (0.03)
FeO†	1.60 (0.08)	1.75 (0.13)	1.61 (0.15)	1.65 (0.13)	1.62 (0.08)	0.78 (0.11)
MnO	n.d.	n.d.	n.d.	n.d.	0.08 (0.04)	0.12 (n.d.)
MgO	0.17 (0.02)	0.17 (0.04)	0.14 (0.06)	0.16 (0.05)	0.19 (0.03)	0.10 (0.01)
CaO	1.30 (0.07)	1.37 (0.16)	1.22 (0.17)	1.29 (0.15)	1.30 (0.04)	0.67 (0.05)
Na_2O	3.75 (0.12)	3.53 (0.11)	3.89 (0.22)	3.73 (0.20)	3.59 (0.08)	3.77 (0.08)
K_2O	2.99 (0.04)	2.92 (0.12)	3.08 (0.37)	2.99 (0.22)	2.88 (0.08)	3.62 (0.09)
Cl	0.11 (0.02)	0.11 (0.02)	0.10 (0.03)	0.10 (0.03)	n.d.	n.d.
Water‡	2.50 (0.96)	2.10 (3.23)	1.25 (0.71)	2.00 (1.93)	1.79 (1.66)	n.d.
n	13	10	10	33	9	20

1 = white ash, Kaipo Lagoon; 2 = white ash, Lake Rotomanuka (core A); 3 = white ash, Lake Rotomanuka (core D); 4 = mean of all analyses 1–3 (=Hinemaiaia Tephra in this study); 5 = Motutere Tephra (lower unit, Opawa Rd: analyses from Froggatt 1982b, p. 320); 6 = Whakatane Ash (analyses from P. C. Froggatt pers. comm. 1984).
n = number of analyses in mean (each analysis was done on a different shard); numbers in parentheses are 1 standard deviation. n.d. = not determined or unavailable. Note that analyses on Hinemaiaia Tephra from the Taupo area are not currently available.
*Glass shards in the 2–4ϕ size fraction were analysed using a JEOL JXA-733 SUPERPROBE at Victoria University of Wellington (Froggatt & Gosson 1982). Analytical conditions were as described in Froggatt (1982b, 1983) including a 10 μm beam diameter, an 8.0 nA beam current, and peak counts of 3 × 10 s (meaned). Repeated analysis of glass standards (KN-18 comendite glass; VG-99 basaltic glass) gave a check on probe calibration and operation. Some samples showed slight Na loss (< 1 wt% oxide), probably due to volatilisation or electron-induced Na^+ migration (Federman & Carey 1980; Froggatt 1983), and only moderate precision for SiO_2, as may occur in probing glasses (e.g., Smith & Westgate 1969).
†All Fe calculated as FeO.
‡Water by difference.

Fig. 3 Chemical composition of the "white ash" glass shown as arbitrary ratios to **(A)** Yellowstone rhyolitic glass standard VG-568, **(B)** histograms of absolute difference between sample pairs where the plot 1-2 compares samples 1 and 2, and so on.



Ave Δ = average difference in ratios; Sim. Coeff. = similarity coefficient for sample pair using all elements analysed (Borchardt et al. 1972); CV = coefficient of variation (Borchardt et al. 1971) (see text). Samples are: 1, Kaipo Lagoon; 2, Lake Rotomanuka (core A); 3, Lake Rotomanuka (core D). Note: The white ash–Whakatane Ash sample pair (analyses 4 & 6, Table 1) similarity coefficient = 0.75, CV = 18.4.

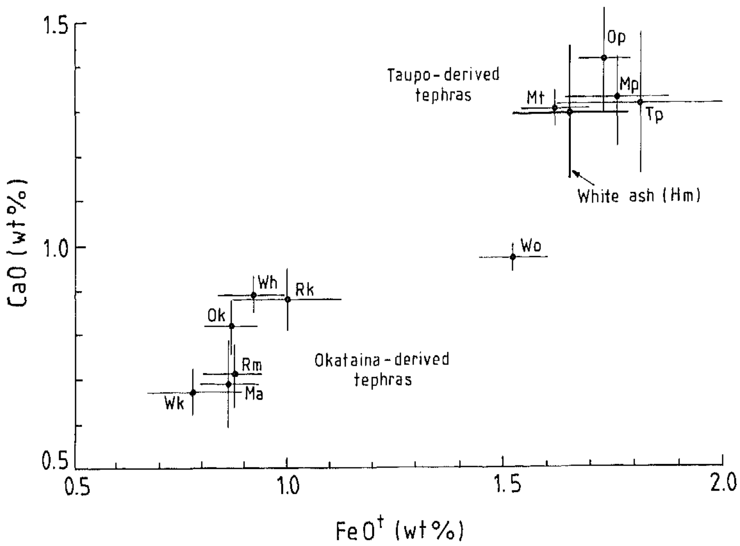


Fig. 4 Plot of CaO versus FeO (total) in glass of some late Quaternary tephras derived from Taupo or Okataina sources. The "white ash" samples (Hm) from Kaipo and Rotomanuka have a Taupo rather than Okataina affinity, and are considered to be correlatives of Hinemaiaia Tephra.

All analyses were by electron microprobe as described in Table 1; bars represent 1 standard deviation from the mean (dots). Tephra abbreviations and sample details (lake and core, number of shards analysed) are: Tp, Taupo Pumice (Lake Rotomanuka core A, 10); Mp, Mapara Tephra (Lake D core 2, 9) (NZMS 260 grid ref. S14/072893); Wo, Whakaipo Tephra (L. Rotomanuka core A, 11); Hm, white ash (=Hinemaiaia Tephra) (column 4, Table 1); Mt, Motutere Tephra (column 5, Table 1); Op, Opepe Tephra (L. Rotomanuka core A, 7) [all from Taupo Volcanic Centre]; Wk, Whakatane Ash (column 6, Table 1); Ma, Mamaku Ash (L. Rotomanuka core A, 14); Rm, Rotoma Ash (L. Rotomanuka core C, 10); Wh, Waiohau Ash (L. Rotomanuka core A, 10); Rk, Rerewhakaaitu Ash (L. Rotomanuka core A, 10); Ok, Okareka Ash (L. Rotomanuka core A, 9) [all from Okataina Volcanic Centre].

tane Ash; at Rotomanuka it is straddled by andesitic tephras dated at 3750 years (above) and 5280 years (below); at Okoroire it underlies a c. 4100 year old andesitic tephra and closely overlies Whakatane Ash.

(5) The glass shards of samples from Rotomanuka and Kaipo are chemically indistinguishable from one another and have major element concentrations typical of Taupo-derived Holocene tephras (Table 1, Fig. 4).

These stratigraphic, chronologic, and compositional similarities together indicate that at all five sites the unnamed rhyolitic tephra is the equivalent eruptive unit, and, furthermore, that it is a distal correlative of Froggatt's (1981a) Hinemaiaia Tephra. Based on this identification, and with both tephras occurring together at four of the five distal sites, it becomes obvious that Hinemaiaia Tephra stratigraphically overlies Whakatane Ash. The tephra originally identified as Hinemaiaia Ash at Poukawa and Tiniroto, and underlying Whakatane Ash, is probably Motutere Tephra. These previous identifications as Hinemaiaia Ash, although strictly correct in terms of the definition of Vucetich & Pullar (1973), are now obsolete in view of Froggatt's (1981a) redefinition and the findings in this study.

The correlation of the unnamed rhyolitic tephra with Hinemaiaia Tephra allows revision of the radiocarbon dates pertaining to it and the closely associated Whakatane Ash, and a reconsideration of the distribution pattern of Hinemaiaia Tephra in the North Island.

CHRONOLOGY OF THE HINEMAIAIA AND WHAKATANE TEPHRAS

Radiocarbon dates relevant to the Hinemaiaia Tephra and Whakatane Ash are summarised in Table 2 and Fig. 5. Four of the dates are deliberately listed in both parts of the table because they apply equally to both tephras. This duality arises because the samples taken for dating bridged the

Table 2 Summary of radiocarbon dates relevant to Hinemaiaia Tephra or Whakatane Ash.

Dating laboratory number[1]	Age (years B.P.) Old half-life	New half-life	Sample material[2]	Location and reference[3]
HINEMAIAIA TEPHRA				
Above[4] (mean = 4360)				
NZ3160	4220 ± 60	4340 ± 70	P	Poukawa (a)
Wk541	4490 ± 70	4620 ± 70	G	Rotomanuka (b)
Below (mean = 4530)				
NZ3161	4800 ± 50	4940 ± 60	P	Poukawa (a)
NZ4574	4650 ± 80	4780 ± 90	C	Near Opawa Rd, Taupo (c)
Wk496	4490 ± 60	4620 ± 60	P	Kaipo (b)
Wk497	4530 ± 60	4660 ± 60	P	Kaipo (b)
Wk542	4470 ± 70	4600 ± 70	G	Rotomanuka (b)
Wk662	4260 ± 140	4390 ± 150	G	Okoroire (b)
Mean age for Hinemaiaia (n = 8): 4490 (std. error ± 140 at p 0.05)				
WHAKATANE ASH				
Above (mean = 4540)				
NZ3161	4800 ± 50	4940 ± 60	P	Poukawa (a)
NZ3948	4600 ± 90	4740 ± 90	P	Poukawa (d)
Wk496	4490 ± 60	4620 ± 60	P	Kaipo (b)
Wk497	4530 ± 60	4660 ± 60	P	Kaipo (b)
Wk662	4260 ± 140	4390 ± 150	G	Okoroire (b)
Below (mean = 4930)				
NZ426	5085 ± 102	5240 ± 110	CW	Terraces pumice pit, Taupo (e)
NZ1066	5180 ± 80	5340 ± 80	C	Haumia Rd, Galatea (e)
NZ1358	4680 ± 100	4820 ± 100	C	Mt Haroharo (f)
NZ3162	5210 ± 80	5370 ± 90	P	Poukawa (a)
NZ3949	4640 ± 90	4770 ± 90	P	Poukawa (d)
Wk501	4860 ± 70	5000 ± 70	P	Kaipo (b)
Wk660	4850 ± 80	4990 ± 80	G	Okoroire (b)
Mean age for Whakatane (n = 12): 4770 (std. error ± 170 at p 0.05)				

[1]NZ = New Zealand Radiocarbon Dating Laboratory (Lower Hutt); Wk = University of Waikato Radiocarbon Dating Laboratory (Hamilton).
[2]C = charcoal; P = peat; G = gyttja (organic lake sediment); CW = charred wood.
[3]a = B. P. Kohn, V. E. Neall & R. B. Stewart (unpublished); b = this study; c = Froggatt (1981a); d = Howorth et al. (1980); e = Grant-Taylor & Rafter (1971); f = Goh & Pullar (1977).
[4]Sample position with respect to tephra (NZ1358 within deposit).

two closely spaced tephras. That Whakatane Ash is older than Hinemaiaia Tephra is now unquestioned because of its established lower stratigraphic position. However, the magnitude of the age difference is less certain because of the various uncertainties in the radiocarbon dating method (Hogg 1982) and possible errors related to variations in sample thickness, position, or type of material being dated. Although there are variations amongst the dates in relation to each tephra, a *t*-test comparison of them nevertheless shows that the mean age for Hinemaiaia Tephra (4490 years) is significantly younger, at a 95% significance level, than that of Whakatane Ash (4770 years). The difference between the means is 280 years; the standard errors indicate that, at $p = 0.05$, the actual difference may be several hundred years greater or less than this figure. A more precise estimate of age difference may be difficult to attain by the ^{14}C method because the errors associated with the dates ultimately limit its resolution (Table 2, Fig. 5). However, more ^{14}C dates from reliable samples may help to resolve some of the discrepancies evident in Fig. 5.

Because Whakatane Ash consists of multiple eruptive units in the Rotorua area (Vucetich & Pullar 1964), it is conceivable that one or more of these units may yet be found to overlie Hinemaiaia Tephra, perhaps at sites proximal to their Okataina source. This possibility clearly requires that the uppermost Whakatane Ash eruptives are several hundred years younger than the lowermost ones.

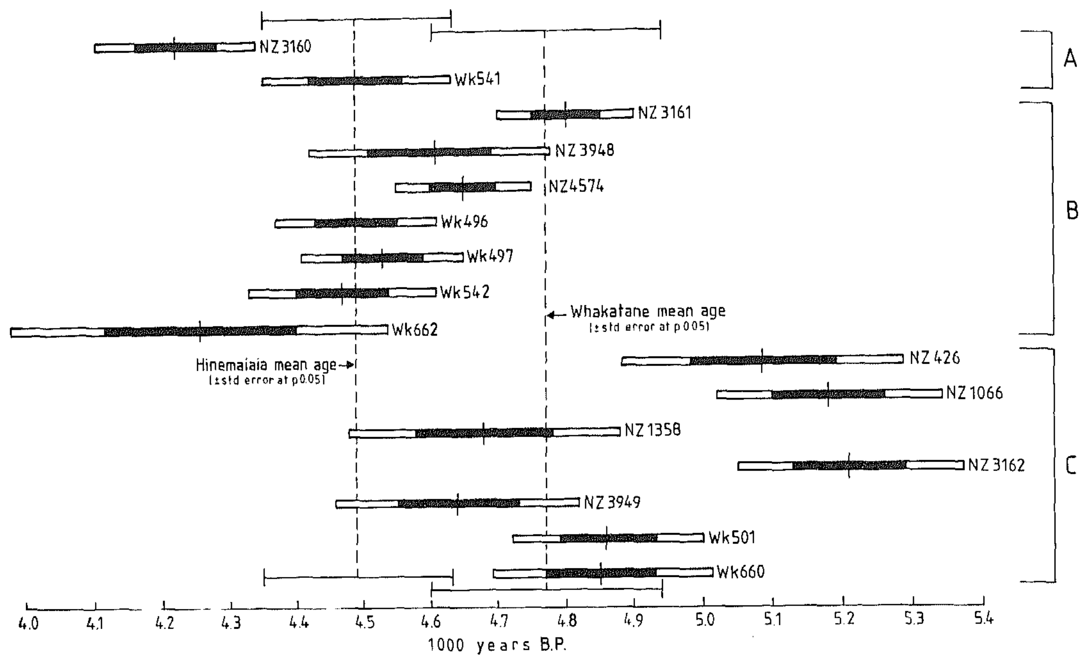


Fig. 5 Comparison of radiocarbon dates (old T½) that apply to Hinemaiaia Tephra or Whakatane Ash (from Table 2). The dates show considerable variation when their error terms are considered. The solid bars represent 1 standard deviation, the open bars 2 standard deviations. The dates are arranged according to their sampling position relative to the Hinemaiaia or Whakatane tephras: A, samples above Hinemaiaia Tephra; B, samples below Hinemaiaia Tephra, or above Whakatane Ash, or both (NZ3948 applies to Whakatane only, NZ4574 and Wk542 to Hinemaiaia only; the rest apply to both tephras); C, samples below Whakatane Ash.

DISTRIBUTION OF THE HINEMAIAIA TEPHRA

The Hinemaiaia Tephra probably originated from the vicinity of a submerged dome-like feature in the southeastern part of Lake Taupo (Froggatt 1981a; Fig. 6). The tephra is about 65 cm thick at its type section (c. 10 km from the postulated vent), and probably has a near-source isopach distribution pattern very similar to that shown for Mototere Tephra (Froggatt 1981a, p. 102) or Hinemaiaia Ash (Vucetich & Pullar 1973, p. 761). However, its demonstrated occurrence at the five widely separated sites in Hawke's Bay, Gisborne, eastern Bay of Plenty, and the Waikato, between 110 and 155 km from the source, shows that it is a much more widespread tephra than previously mapped. This adds support to the studies on other plinian deposits that have indirectly deduced much larger dispersion areas than their isopachs indicated (e.g., Walker 1980, 1981b). Because the eruption of Hinemaiaia Tephra apparently lacked an ignimbritic component (Froggatt 1981a; cf. Vucetich & Pullar 1973), the distal deposits studied here presumably derive from plinian fallout rather than co-ignimbrite ash fallout. The occurrence of Hinemaiaia Tephra in the Waikato area, well upwind of the vent, and the roughly circular shape of the tentative 10 mm isopach in Fig. 6, suggests that it may also be found in suitable sediments in the Wanganui and Taranaki regions. Assuming an exponential decrease in thickness (Froggatt 1982a), the Hinemaiaia Tephra is likely to be only a few millimetres thick at distances of c. 200–250 km from Lake Taupo.

Dispersive power

The area, D, enclosed by the $0.01T_{MAX}$ isopach (where T_{MAX} is the maximum thickness of the deposit) is indicative of the dispersive power of an eruption (Walker 1973, 1980). Assuming that T_{MAX} for Hinemaiaia Tephra is similar to its type section thickness of c. 650 mm (it may be a little more or less than this, allowing for the uncertain vent position), then the c. 10 mm isopach in Fig. 6, admittedly based on sparse data, may be regarded as a crude approximation of the $0.01T_{MAX}$ isopach (i.e.,

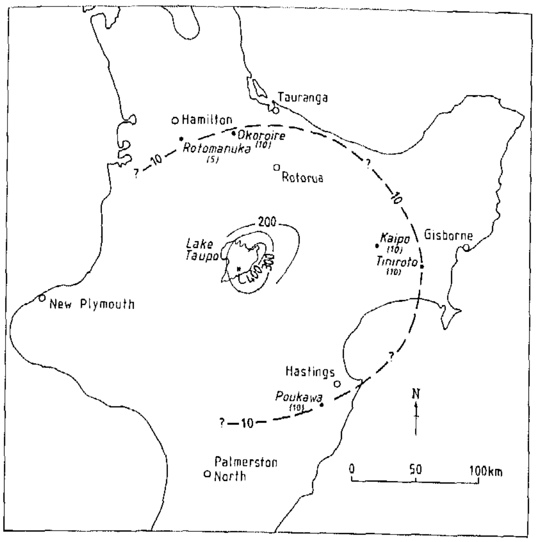


Fig. 6 Possible distal distribution of the Hinemaiaia Tephra. The dashed line is a tentative c. 10 mm isopach of Hinemaiaia Tephra based on its estimated thickness at the five sites as indicated. Isopachs (in millimetres) around Lake Taupo are of the Hinemaiaia Ash (Vucetich & Pullar 1973, p. 761). Hinemaiaia Tephra's probable source location in Lake Taupo is indicated by an asterisk (Froggatt 1981a).

c. 6.5 mm). On this basis, and using a circular distribution of radius 110 km, a D (dispersal index) value of about 40 000 km² is obtained. Even if this figure is overestimated by 25%, comparison with D values in the literature (Nairn 1980; Walker 1980, 1981b) suggests that the Hinemaiaia Tephra represents an "above average" plinian event of comparable ranking to the Waimihia Lapilli eruption (D ≈ 30 000 km²), being surpassed only by the Taupo Pumice ultraplinian eruption (D ≈ 100 000 km²). The Hatepe Lapilli eruption (D ≈ 10 000 km²) represents an "average" plinian event (Walker 1980), as presumably does the Rotorua Ash eruption (D ⩾ 10 000 km²: Nairn 1980). The implication is that the Hinemaiaia Tephra eruption was extremely powerful and had a very high eruptive 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 (Walker 1973, 1981a; Wilson et al. 1978). The generally fine ash size grade and the low phenocryst content of Hinemaiaia Tephra at its distal localities supports the deduction of such a high eruption column (Walker 1980, 1981a).

Walker (1981b, p. 323) commented that it was remarkable that the two latest major eruptions (Taupo, Waimihia) from the Taupo Volcanic Centre produced exceptional plinian deposits. From the above inferences regarding the above average status of Hinemaiaia Tephra, it seems that such exceptional plinian eruptions are perhaps not so rare.

CONCLUSIONS

The stratigraphic and chronologic relationships of Hinemaiaia Tephra and Whakatane Ash, uncertain from prior studies in the Taupo area, have been resolved through the examination of distal tephras preserved within organic deposits at five sites in eastern and northern North Island. The existence of a disputed unnamed rhyolitic tephra, previously reported between the Waimihia and Whakatane tephras at two of the sites (Tiniroto and Poukawa), is confirmed by its unequivocal occurrence as a primary tephra deposit at the other three sites (Kaipo, Rotomanuka, and Okoroire). Based on its stratigraphic position, composition (ferromagnesian mineralogy and glass chemistry), and ^{14}C chronology, this tephra, derived from the Taupo Volcanic Centre, is established as a distal correlative of Hinemaiaia Tephra (as defined by Froggatt 1981a). It stratigraphically overlies Whakatane Ash at all of the sites except Rotomanuka where the latter tephra is not evident as a megascopic layer. The tephra previously identified as Hinemaiaia Ash (following the definition of Vucetich & Pullar 1973) at Tiniroto and Poukawa, and underlying Whakatane Ash, is probably Motutere Tephra (Froggatt 1981a).

The 10 new ^{14}C dates obtained on peat or gyttja associated with the Hinemaiaia and Whakatane tephras permit revision of their eruption ages: Hinemaiaia Tephra has a mean age of c. 4500 years, Whakatane Ash c. 4800 years, with standard errors near c. 150 years (Table 2). The Motutere Tephra has a mean age of c. 5400 years (Froggatt 1981a).

Based on the distal occurrences described here, the Hinemaiaia Tephra has a considerably more widespread distribution, probably from coast to coast across central North Island, than previously mapped. Such a large dispersal area for this tephra (perhaps of the order of 10^4 km²) as a sheet-forming deposit suggests that it may have been deposited by a very powerful, above average plinian event (Walker 1980) with an eruption column probably exceeding 30 km in height.

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