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Stratigraphy and chronology of a 15 ka sequence of multi-sourced silicic tephras in a montane peat bog, eastern North Island, New Zealand

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Abstract We document the stratigraphy, composition, and chronology of a succession of 16 distal, silicic tephra layers interbedded with lateglacial and Holocene peats and muds up to c. 15 000 radiocarbon years (c. 18 000 calendar years) old at a montane site (Kaipo Bog) in eastern North Island, New Zealand. Aged from 665 ± 15 to 14 700 ± 95 ^{14}C yr BP, the tephras are derived from six volcanic centres in North Island, three of which are rhyolitic (Okataina, Taupo, Maroa), one peralkaline (Tuhua), and two andesitic (Tongariro, Egmont). Correlations are based on multiple criteria: field properties and stratigraphic interrelationships, ferromagnesian silicate mineral assemblages, glass-shard major element composition (from electron microprobe analysis), and radiocarbon dating. We extend the known distribution of tephras in eastern North Island and provide compositional data that add to their potential usefulness as isochronous markers. The chronostratigraphic framework established for the Kaipo sequence, based on both site-specific and independently derived tephra-based radiocarbon ages, provides the basis for fine-resolution paleoenvironmental studies at a climatically sensitive terrestrial site from the mid latitudes of the Southern Hemisphere. Tephras identified as especially useful paleoenvironmental markers include Rerewhakaaitu and Waiohau (lateglacial), Konini (lateglacial–early Holocene), Tuhua (middle Holocene), and Taupo and Kaharoa (late Holocene).

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INTRODUCTION

The transition from the last cold stage to the present interglacial, the marine oxygen isotope stage 2/1 boundary, or "lateglacial", has become one of the most intensively studied intervals of the Quaternary Period. This is because lateglacial records of inferred environmental change potentially may be examined with finer temporal resolution, and dated more precisely, than in earlier parts of the Quaternary, thus providing a means for understanding how Earth and atmospheric processes interact during such cold-to-warm climatic transitions (Lowe & Walker 1997; Björck et al. 1998). Similarly, the nature and timing of environmental changes in the present interglacial (Holocene) have attracted growing attention because recent studies of earlier interglacials show marked and rapid paleoclimatic fluctuations in these periods (e.g., Dansgaard et al. 1993; Seidenkrantz et al. 1995), implying that the Holocene may also be less stable climatically than previously assumed (e.g., Bond et al. 1997; Lowe et al. 1997). It is now recognised that to make further advances in detecting and understanding such short-term paleoclimatic changes for the lateglacial and Holocene periods requires the availability of proxy records with certain minimal features: sites and the records they yield must be sensitive to climatic change, they must be capable of being sampled at an appropriate high-resolution scale, and they must be chronologically well constrained using radiometric or incremental dating methods, ideally also containing age-equivalent stratigraphic markers, such as tephra layers, to test the veracity of site-specific radiometric dates and to facilitate correlation on a regional to global scale.

We have identified such a site in New Zealand that meets all these criteria. The site, at Kaipo Bog, near Lake Waikaremoana, eastern North Island (Fig. 1), comprises a c. 15 000 radiocarbon (^{14}C) year long sequence of peat and mud deposits interbedded with 16 macroscopic, silicic tephra layers derived from 6 separate volcanic centres. Located at a climatically sensitive montane-subalpine environment (Newnham & Lowe in press), the site has the potential to provide a fine-resolution record of paleoclimatic changes for the lateglacial–Holocene at a middle latitudinal, maritime location in the Southern Hemisphere, and therefore to contribute to the attainment of a gobal view of the character and timing of the last glacial–interglacial transition, including the critical "Younger Dryas" cooling interval (Greenland Stadial-1 of Björck et al. 1998) (e.g., Denton & Hendy 1994; McGlone 1995; Taylor et al. 1997), and additionally of Holocene climatic variability. In this paper,

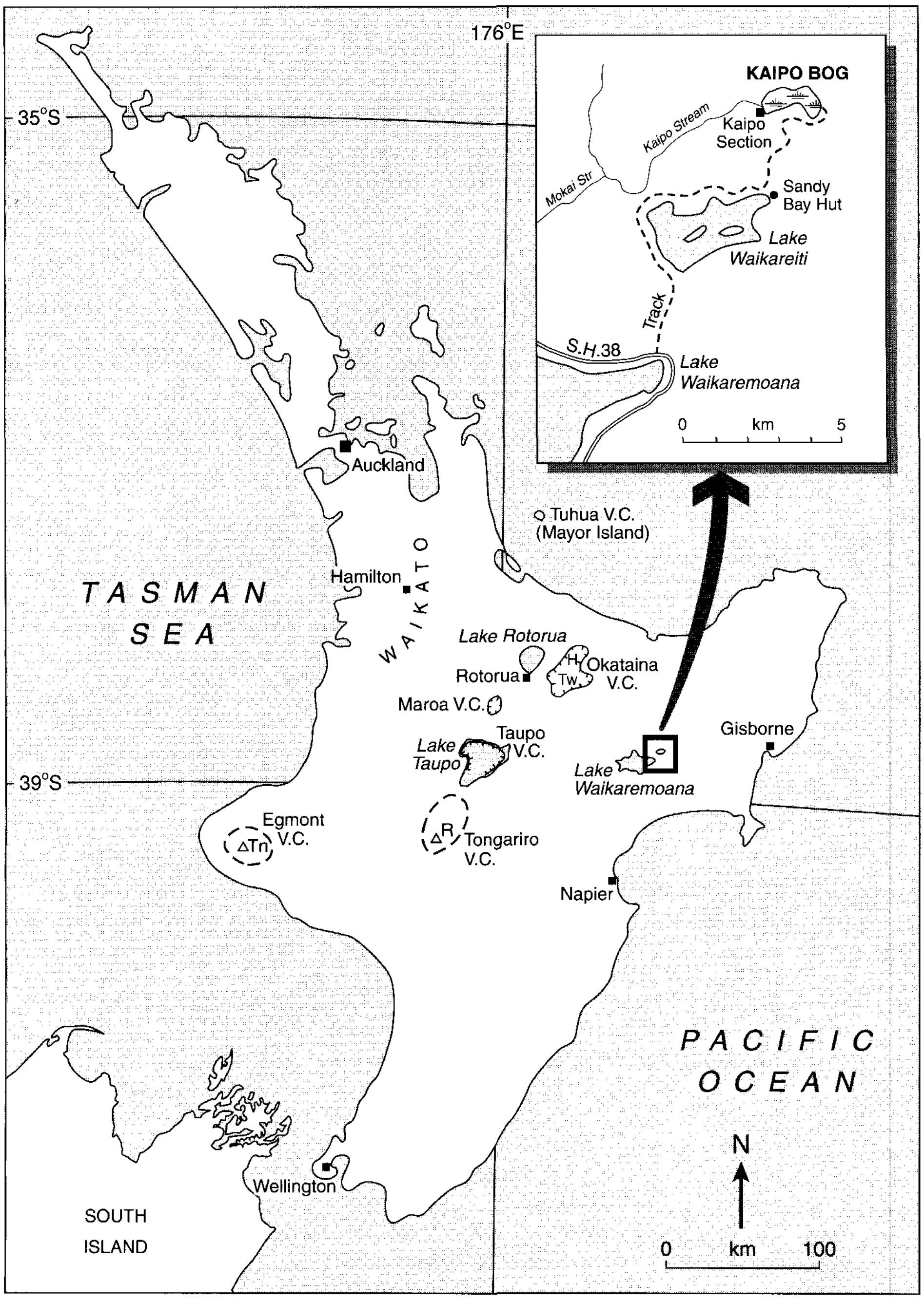

Fig. 1 Location of Kaipo Bog, North Island, New Zealand, and source volcanic centres (V.C.) of the tephras identified at Kaipo (after Froggatt & Lowe 1990). H, Haroharo volcano; Tw, Mt Tarawera volcano; R, Mt Ruapehu volcano; Tn, Mt Taranaki/Mt Egmont volcano; S.H., State Highway.

our primary aim is to document the tephrostratigraphy and adjunct chronology, based on radiocarbon dating, of the Kaipo Bog site to provide the chronostratigraphic framework essential for detailed paleoenvironmental studies. These studies, currently in progress, include analyses of pollen, stable carbon isotopes, and testate amoebae, and will be reported elsewhere (e.g., Newnham & Lowe in prep.). Such studies will also permit assessment of the potential environmental impacts of tephra fall at a site well beyond the proximal hazard zone of New Zealand's active volcanic centres (e.g., see Wilmshurst & McGlone 1996; Giles et al. 1999).

In addition to providing a tephrochronological framework, our study extends the known geographic distribution of tephras in eastern North Island, which is important for modelling the magnitude and style of tephra-generating eruptions, and for broader volcanic systems' interpretations (e.g., Wilson 1993; Houghton et al. 1995; Nairn et al. 1998; Lowe & Newnham 1999; Shane in press). We also report new major element analyses, obtained by electron microprobe, on glass from the tephras, together with mineralogical analyses, which thereby add to their potential usefulness as isochronous stratigraphic markers. The study builds on earlier stratigraphic work at Kaipo Bog by Lowe & Hogg (1986).

KAIPO BOG AND ENVIRONS

Kaipo Bog is a 73 ha peat bog lying at an altitude of 980 m above sea level to the north of Lake Waikareiti in Te Urewera

National Park, Huiarau Range, North Island, at 38°40′S and 177°10′E (Fig. 1). It has formed within an infilled basin at the trailing edge of a 53 km^2 area of landslide debris, the result of a massive landsliding event from the north (Ward 1995). Sediment derived from the surrounding debris and bedrock slopes, which are composed of sandstone and soft, blue-grey siltstone or mudstone (Moore 1979), appears to have substantially infilled the basin before peat bog development began. Except on steep or unstable slopes, generally shallow (≤c. 0.6 m) tephra-fall deposits mantle the sedimentary rocks in the area (Rijske 1979).

The bog is the largest of a group of natural enclosed clearings in the area that form small peaty wetlands and lakelets within montane-subalpine beech forest (mainly *Nothofagus menziesi* and *N. fusca*) and shrubland (New Zealand Forest Service 1969; McKelvey 1973; Newnham et al. 1998a). It is essentially an ombrogenous shrub bog dominated by rushes (mainly *Empodisma minus*) and ferns (*Gleichenia dicarpa*), with occasional *Sphagnum* spp., which form low hummocks amidst numerous small, permanent pools (Rogers 1984; Lowe & Hogg 1986). Modern pollen spectra at Kaipo Bog reflect local vegetation sources but also include pollen derived from lowland-montane mixed podocarp-angiosperm-beech forest at lower altitudes as well as from grassland-shrubland communities at or above the present treeline near 1370 m elevation. Because the altitudinal zonation of vegetation in these uplands is controlled largely by temperature (McKelvey 1973), a pollen record from Kaipo Bog would therefore serve as an indicator of past temperature change in the region (Newnham & Lowe in press).

A small stream and its tributaries draining the western end of Kaipo Bog have incised the bog surface to expose a series of vertical sections comprising peats and inorganic muds with interbedded tephra layers. The stratigraphy and chronology of one of these sections was studied by Lowe & Hogg (1986). Subsequent fieldwork has revealed a further three adjacent sections extending stratigraphically below that studied by Lowe & Hogg (1986), and containing tephra beds additional to those recognised earlier. The full sequence is difficult to see in any one section because of differing water-table levels and because fallen trees and other debris covered with forest undergrowth restrict access. However, the physical characteristics of the tephra layers and other lithological features, together with stratigraphic relationships, allow the three closely spaced sections (they are only c. 5–10 m apart) to be readily linked to one another. This has enabled us to construct a composite stratigraphic column c. 4.4 m high extending from the modern peat surface to c. 15 000 ^{14}C yr BP at the base (Fig. 2). The sequence is centred on grid reference sheet W18/739717 (based on the 1000 m grid of the NZMS 260 1:50 000 topographical map series).

STRATIGRAPHY AND CORRELATION OF TEPHRAS

The Kaipo sequence, from top to bottom, comprises an upper unit of black peat (0–2.75 m depth) grading into a unit of brown peat (2.75–2.95 m), a pale brownish-grey mud unit containing organic "stringers" and two peaty layers up to 100 mm thick (2.95–3.5 m), and a lower unit of black peat (3.5–4.25 m) that grades to a basal unit of olive-blue sandy mud containing very thin organic bands (4.25–4.42 m) (Fig. 2). Interbedded with these sediments are the 16 macroscopic tephra layers. These range from c. 10 to 280 mm in thickness, although thicknesses may vary laterally (Fig. 2). They are predominantly of ash grade but some are dominated by fine lapilli, and some are distinctively bedded (Table 1). The Waiohau Tephra comprises a layer c. 220 mm thick overlain in places by a reworked, but compositionally identical, layer c. 200 mm thick (see analyses 6a–6c in Table 2, below). The total thickness of the tephras is c. 1.6 m. The tephras newly identified here since the work of Lowe & Hogg (1986) are the Tuhua, Mamaku, Konini, Waiohau, Puketarata, and Rerewhakaaitu Tephras. However, we did not find Mapara Tephra (equivalent to Unit-X of Wilson 1993) reported by Lowe & Hogg (1986): it may have been misidentified in the original study or it has been eroded and is missing from the new site.

Correlation of the tephra layers is based on multiple criteria including field appearance (physical properties) and stratigraphic position, analysis of ferromagnesian silicate mineral assemblages by petrological microscope, and analysis of glass-shard major element compositions by electron microprobe (Tables 1, 2). Identifications were supported by radiocarbon dating (see Chronology section below). Most of the glass compositional analyses derived from electron microprobe (Table 2) were calculated using a procedure different from that employed before 1995 at the Analytical Facility, Victoria University of Wellington (Manning 1995). The result is that, in general, silica totals tend to be slightly lower (by c. 0.5–1.0 wt%) than those obtained under the previous method, and other major elements except K_2O tend to be commensurately slightly greater (especially Na_2O, TiO_2). Consequently, comparisons between glass analyses made on tephras before and after 1995 need to be judged in this light.

Most of the tephras at Kaipo Bog are derived from the rhyolitic volcanic centres of Okataina (six tephras), Taupo (six tephras), and Maroa (one tephra); one tephra is derived from the peralkaline Tuhua (Mayor Island) centre, and one is derived from each of the andesitic Tongariro and Egmont centres (Fig. 1; Froggatt & Lowe 1990). There are relatively few systematic microprobe-derived major element glass analyses available for andesitic tephras (in contrast to rhyolitic tephras, e.g., see Stokes et al. 1992), and such analyses tend to show relatively wide variations (Lowe 1988a, b; Stokes & Lowe 1988; Froggatt & Rogers 1990; Eden & Froggatt 1996; Donoghue et al. 1999). Some of this variation relates to magma mingling or fractionation (e.g., Donoghue et al. 1995a, 1999; Nakagawa et al. 1998; Price et al. 1999); some may relate to the effects of plagioclase microlites on the electron microprobe analyses (Lowe 1988b; Shane in press). Thus, the correlations for andesitic tephras are provisional. Criteria for specific correlations with named eruptives are summarised below.

Okataina-derived tephras

These are named here using the nomenclature of Froggatt & Lowe (1990), and consist of the Kaharoa, Whakatane, Mamaku, Rotoma, Waiohau, and Rerewhakaaitu Tephras. They are dominated mineralogically by either biotite (Kaharoa, Rerewhakaaitu) or cummingtonite (Whakatane, Rotoma), or they comprise assemblages of hornblende plus

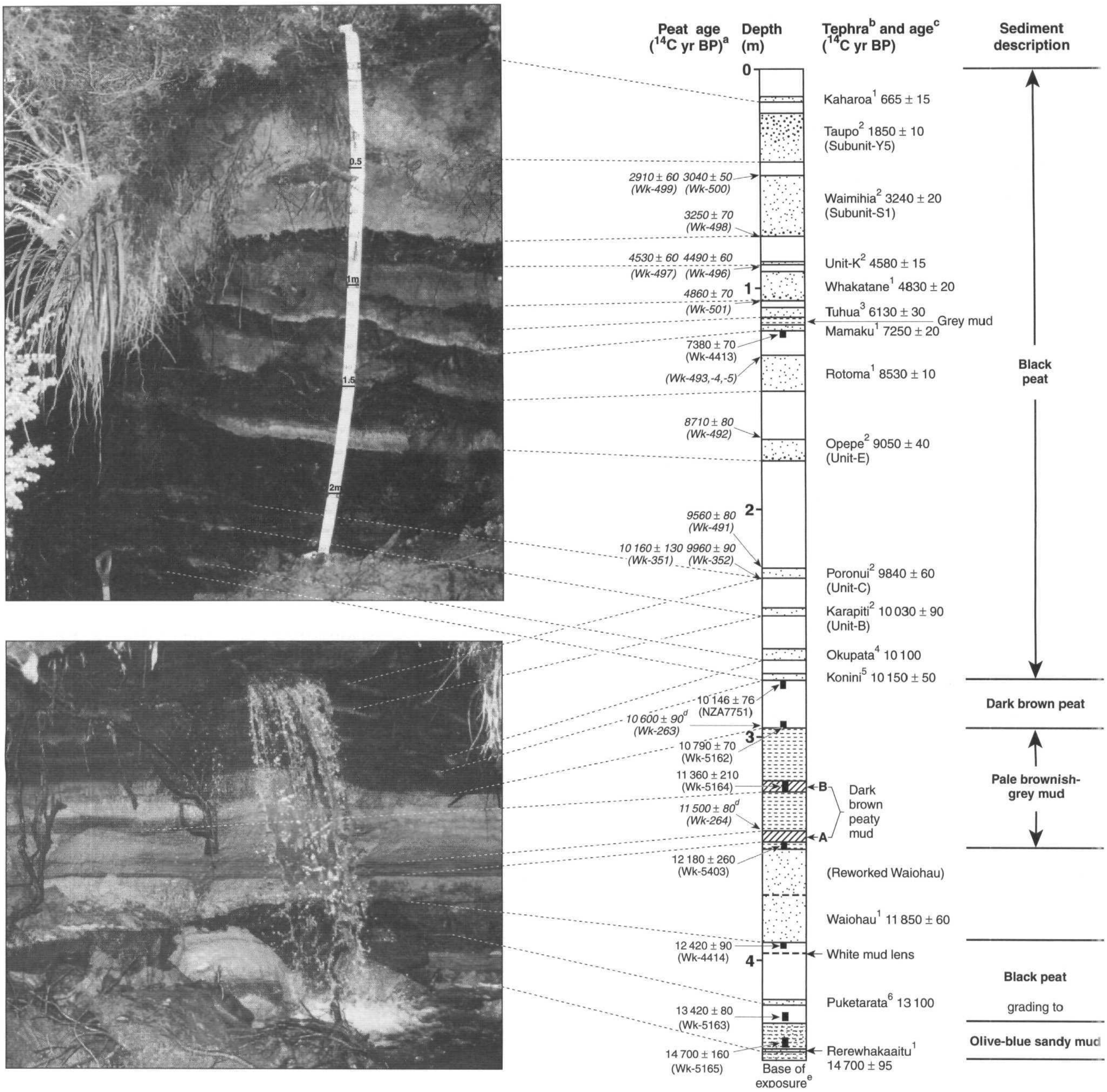

Fig. 2 Tephrostratigraphy and chronology of the Kaipo Bog sequence. [a]Ages in italics are from Lowe & Hogg (1986), others this study (Table 3); [b]named tephra units derived from Okataina (1), Taupo (2), Tuhua (3), Tongariro (4), Egmont (5), or Maroa (6) Volcanic Centres (Fig. 1); [c]ages of tephras ±1 SD (see text and Table 1); [d]sampling juxtapositions of these ages (from Lowe & Hogg 1986) are approximate; [e]the base of the section is not necessarily the base of the post-landslide basin-infilling deposits. N.B. Waimihia and Unit-K ages should read 3230 ± 20 and 4510 ± 20 ^{14}C yr BP. respectively.

hypersthene ± augite (Waiohau, Mamaku), all of which are characterisitic for these eruptives (Lowe 1988a, b; Froggatt & Lowe 1990). Glass shard major element compositions (anal. 1–7, Table 2), all rhyolitic*, are consistent with those for Okataina-sourced eruptives and with individual (named) tephra formations (Green & Lowe 1985; Lowe 1986, 1988a, b; Stokes & Lowe 1988; Froggatt & Rogers 1990; Pillans & Wright 1992; Stokes et al. 1992; Eden & Froggatt 1996; Lowe et al. 1998). Ranges for selected oxides (mean values) are SiO_2 77.4–78.1%, TiO_2 0.1–0.2%, FeO_{total} 0.8–1.1%, MgO 0.1–0.2%, and CaO 0.5–1.0% (TiO_2 is notably high, 0.22%, in Waiohau Tephra).

*Classifications of glass are based on the IUGS total alkali-silica diagram of Le Bas et al. (1986).

Taupo-derived tephras

These are named according to the terminology both of Froggatt & Lowe (1990) and Wilson (1993). They comprise Taupo (Subunit-Y5 of Wilson 1993), Waimihia (Subunit-S1), Unit-K (previously called a "Hinemaiaia" eruptive: Lowe 1986; Lowe & Hogg 1986), Opepe (Unit-E), Poronui (Unit-C), and Karapiti (Unit-B) Tephras. All are dominated by hypersthene with minor augite ± hornblende (Table 1),

Table 1 Stratigraphy and selected characteristics of tephra deposits at Kaipo Bog.

Tephra name (*symbol*)	Source[a]	Age (^{14}C yr BP)[b]	Thickness (mm)	General description[c]	Ferromagnesian mineralogy[d]
Kaharoa (*Ka*)	OK-Tw	665 ± 15 (*n* = 14)	20	White fine ash with sparse hard, fine lapilli; "sugary" appearance in peat where disseminated	Bio ≥ Hyp > Hbe, Aug
Taupo (*Tp*) [Subunit-Y5][e]	TP	1850 ± 10 (*n* = 41)	220	Orange fine lapilli over yellowish coarse ash	Hyp >> Aug
Waimihia (*Wm*) [Subunit-S1]	TP	3230± 20 (*n* = 17)	280	Greyish-white medium to fine ash (top 50 mm) over "blotchy" grey medium ash over yellowish-reddish fine lapilli and coarse ash at base	Hyp >> Aug
Unit-K (-*K*)	TP	4510 ± 20 (*n* = 13)	10	White fine ash	Hyp >> Aug
Whakatane (*Wk*)	OK-H	4830 ± 20 (*n* = 21)	140	Firm, compact reddish-brown/orange fine ash with coarse ash base (lower 20 mm), wavy boundary	Cgt >> Hyp, Hbe, Aug
Tuhua (*Tu*)	TU	6130 ± 30 (*n* = 10)	40	Olive-grey medium ash (gritty, soft, putty-like)	Aeg >> Hyp
Mamaku (*Ma*)	OK-H	7250 ± 20 (*n* = 22)	30	White-cream fine and medium ash, wavy boundary	Hbe ≥ Hyp >> Aug, ?Cgt
Rotoma (*Rm*)	OK-H	8530 ± 10 (*n* = 45)	160	Reddish-brown medium ash over firm, yellow fine ash at base, wavy boundary (thickness of deposit varies from c. 70–200 mm)	Cgt >> Hbe, Hyp
Opepe (*Op*) [Unit-E]	TP	9050 ± 40 (*n* = 10)	90	Reddish-brown and cream fine ash (top 30 mm) over medium to coarse reddish-yellow ash	Hyp >> Aug
Poronui (*Po*) [Unit-C]	TP	9840 ± 60 (*n* = 3)	40	Yellowish-brown medium ash	Hyp >> Aug
Karapiti (*Kp*) [Unit-B]	TP	10030 ± 90 (*n* = 2)	30	Cream firm, fine ash (lensoidal)	Hyp >> Aug, Hbe
Okupata (*Oa*)[f] [Taurewa]	TG-R	10100	50	Cream-grey firm, fine ash (lensoidal)	Opx[g] > Cpx
Konini (*Ko*) [Egmont-11]	EG-Tn	10150 ± 50 (*n* = 4)	20	Reddish-brown fine to very fine ash	Hbe ≥ Cpx > Opx
Waiohau (*Wh*)	OK-Tw	11850 ± 60 (*n* = 12)	420	*Upper unit* (200 mm, reworked tephra): white fine to medium ash over pale orange-grey, slightly laminated, coarse ash (variable thickness); *Lower unit* (220 mm, primary tephra): interlayered cream and grey fine ash beds	Hyp > Hbe, Aug
Puketarata (*Pk*)	MA	13100	10	White fine to medium ash (variable thickness 10–20 mm); black biotite flakes visible in hand specimen	Bio >> Hbe, Hyp
Rerewhakaaitu (*Rk*)	OK-Tw	14700 ± 95 (*n* = 4)	10	Bluish-grey coarse ash; black biotite flakes visible in hand specimen	Bio >> Hbe, Hyp >> Aug

[a]OK, Okataina Volcanic Centre (-Tw, Mt Tarawera volcano; -H, Haroharo volcano); TP, Taupo Volcanic Centre; TU, Tuhua Volcanic Centre (Mayor I.); EG, Egmont Volcanic Centre (-Tn, Mt Taranaki volcano); TG, Tongariro Volcanic Centre (-R, Mt Ruapehu volcano); MA, Maroa Volcanic Centre.

[b]Conventional radiocarbon ages modified after Froggatt & Lowe (1990), Wilson (1993), Alloway et al. (1995), and Lowe et al. (1998); ages on Okupata and Puketarata Tephras are estimated from sedimentation rates (see text). *n*, number of individual ages used to obtain error-weighted mean.

[c]See also Lowe & Hogg (1986). Fine ash, <0.1 mm; medium ash, 0.1–0.5 mm; coarse ash, 0.5–2 mm; fine lapilli, 2–5 mm (approx.).

[d]Dominant minerals in the magnetic fraction (separated by Frantz electromagnetic separator). Bio, biotite; Hyp, hypersthene; Aug, augite; Hbe, calcic hornblende; Cgt, cummingtonite; Aeg, aegirine; Opx, orthopyroxene; Cpx, clinopyroxene. All tephras contain Fe-Ti oxides (opaque minerals); the Okataina-derived tephras additionally contain zircon. Glass, plagioclase feldspar ± quartz predominate in non-magnetic fractions in all tephras. See also Lowe & Hogg (1986).

[e]Names in square brackets are alternatives for each tephra (see text).

[f]Provisionally correlated with Okupata Member (?Ok_3) of Taurewa Formation (Donoghue et al. 1999).

[g]The orthopyroxene here consists of two types, one pale green, the other dark orange and strongly zoned (under polarising microscope, plain light).

Table 2 Electron microprobe analyses[a] of glass from tephras in the Kaipo Bog area.

	Okataina-derived tephras								
	Ka		*Wk*	*Ma*	*Rm*	*Wh*			*Rk*
Anal no.[b]	1	2	3	4	5	6a	6b	6c	7
SiO_2	77.36 (0.09)	77.44 (0.28)	78.09 (0.27)	78.06 (0.26)	78.07 (0.33)	77.62 (0.30)	77.84 (0.20)	77.73 (0.27)	77.56 (0.48)
Al_2O_3	12.85 (0.17)	12.83 (0.14	12.36 (0.15)	12.30 (0.13)	12.32 (0.18)	12.73 (0.22)	12.60 (0.17)	12.67 (0.20)	12.85 (0.30)
TiO_2	0.11 (0.03)	0.12 (0.03)	0.14 (0.04)	0.16 (0.05)	0.16 (0.05)	0.23 (0.05)	0.20 (0.06)	0.22 (0.06)	0.12 (0.03)
FeO^c	0.89 (0.08)	0.88 (0.10)	0.82 (0.11)	0.93 (0.07)	0.92 (0.11)	1.08 (0.09)	1.05 (0.16)	1.07 (0.12)	0.91 (0.12)
MgO	0.09 (0.03)	0.08 (0.03)	0.13 (0.04)	0.13 (0.03)	0.15 (0.03)	0.17 (0.05)	0.13 (0.04)	0.15 (0.04)	0.11 (0.05)
CaO	0.53 (0.10)	0.52 (0.07)	0.71 (0.06)	0.80 (0.07)	0.82 (0.05)	0.92 (0.11)	0.98 (0.06)	0.95 (0.09)	0.83 (0.08)
Na_2O	3.98 (0.04)	3.89 (0.13)	3.89 (0.13)	3.83 (0.17)	4.00 (0.07)	4.04 (0.16)	4.09 (0.14)	4.07 (0.15)	3.62 (0.14)
K_2O	4.05 (0.13)	4.09 (0.25)	3.71 (0.08)	3.63 (0.10)	3.39 (0.14)	3.06 (0.18)	2.97 (0.06)	3.02 (0.14)	3.82 (0.36)
Cl	0.16 (0.03)	0.16 (0.02)	0.16 (0.03)	0.17 (0.05)	0.18 (0.05)	0.14 (0.01)	0.14 (0.05)	0.14 (0.04)	0.18 (0.03)
Water[d]	6.39 (1.05)	6.31 (1.39)	4.52 (1.50)	4.42 (1.07)	4.24 (0.77)	4.01 (1.42)	3.83 (1.56)	3.92 (1.44)	3.41 (1.40)
n	9	11	11	11	10	7	7	14	15

	Taupo-derived tephras							
	Tp (Y5)		*Wm (S1)*	*Unit-K*		*Op (E)*	*Po (C)*	*Kp (B)*
	8	9	10	11a	11b	12	13	14
SiO_2	74.88 (0.46)	75.79 (0.31)	76.22 (0.19)	76.31 (0.32)	76.90 (0.23)	75.99 (0.40)	76.49 (0.56)	76.14 (0.46)
Al_2O_3	13.52 (0.18)	13.23 (0.13)	13.03 (0.19)	12.99 (0.27)	12.99 (0.10)	12.98 (0.22)	12.76 (0.27)	13.35 (0.27)
TiO_2	0.30 (0.11)	0.24 (0.04)	0.21 (0.05)	0.24 (0.03)	0.19 (0.03)	0.22 (0.04)	0.21 (0.06)	0.24 (0.06)
FeO^c	2.07 (0.14)	1.83 (0.11)	1.79 (0.11)	1.70 (0.19)	1.60 (0.08)	1.85 (0.14)	1.68 (0.13)	1.65 (0.11)
MgO	0.26 (0.06)	0.21 (0.02)	0.19 (0.04)	0.17 (0.02)	0.17 (0.02)	0.24 (0.06)	0.20 (0.04)	0.20 (0.05)
CaO	1.57 (0.14)	1.37 (0.11)	1.43 (0.10)	1.41 (0.14)	1.30 (0.07)	1.63 (0.13)	1.45 (0.19)	1.45 (0.11)
Na_2O	4.29 (0.16)	4.37 (0.19)	4.11 (0.10)	4.13 (0.11)	3.75 (0.12)	3.90 (0.08)	3.88 (0.15)	4.05 (0.14)
K_2O	2.95 (0.25)	2.79 (0.14)	2.85 (0.15)	2.92 (0.17)	2.99 (0.04)	3.01 (0.11)	3.18 (0.20)	2.77 (0.11)
Cl	0.15 (0.03)	0.17 (0.03)	0.16 (0.03)	0.14 (0.03)	0.11 (0.02)	0.18 (0.05)	0.16 (0.03)	0.16 (0.03)
Water[d]	5.97 (1.13)	5.60 (0.90)	4.20 (0.52)	3.17 (0.81)	2.50 (0.96)	5.52 (1.23)	5.05 (1.63)	5.26 (2.32)
n	10	9	10	9	13	11	10	11

	Maroa-, Tuhua-, Tongariro-, and Egmont-derived tephras					
	Pk		*Tu*	*Oa*	*Ko*	
	15	16	17	18	19a	19b
SiO_2	77.82 (0.33)	78.49 (0.50)	74.56 (0.37)	68.81 (1.26)	65.37 (0.37)	59.07 (2.13)
Al_2O_3	12.59 (0.20)	12.28 (0.10)	9.48 (0.27)	15.64 (0.89)	17.43 (0.53)	20.49 (2.97)
TiO_2	0.08 (0.05)	0.08 (0.02)	0.29 (0.08)	0.79 (0.11)	0.72 (0.09)	0.59 (0.17)
FeO^c	0.82 (0.06)	0.90 (0.10)	5.54 (0.38)	3.41 (0.26)	3.25 (0.54)	3.88 (0.89)
MgO	0.08 (0.02)	0.07 (0.03)	0.07 (0.02)	0.90 (0.10)	1.04 (0.26)	1.67 (0.44)
CaO	0.66 (0.06)	0.64 (0.04)	0.27 (0.04)	3.38 (0.72)	2.79 (0.50)	7.08 (1.79)
Na_2O	3.56 (0.21)	3.23 (0.38)	5.34 (0.25)	3.94 (0.17)	4.98 (0.37)	4.64 (0.17)
K_2O	4.20 (0.13)	4.17 (0.48)	4.25 (0.19)	2.97 (0.17)	4.24 (0.23)	2.46 (0.97)
Cl	0.19 (0.03)	0.15 (0.03)	0.22 (0.04)	0.16 (0.04)	0.19 (0.04)	0.13 (0.10)
Water[d]	1.99 (1.29)	5.07 (1.09)	3.38 (1.00)	3.34 (2.28)	2.36 (0.78)	1.10 (0.04)
n	11	12	11	11	8	2

[a] Means and standard deviations (in parentheses) of *n* analyses (individual glass shards) normalised to 100% loss-free (wt%). Analyses by wavelength-dispersive Jeol JXA-733 Superprobe at the Analytical Facility, Victoria University of Wellington, were undertaken by D. A. Manning (all except *11b* and *16*) using various glass and elemental standards to correct for machine drift, defocused beam diameter 10–15 µm, current 8 nA, and accelerating voltage 15 kV (see Froggatt 1983; Lowe 1988b; Manning 1995). Analyses were calculated (except *11b, 16*) from 11 × 2 s counts across the peak, curve integrated; anal. (*11b*) and (*16*) (analyst D. J. Lowe) were calculated from 3 × 10 s count times at the peak, meaned. Tephra abbreviations are given in Table 1.

[b] All analyses are on samples from the Kaipo Bog section except anal. (*2*) and (*9*) which are from nearby Lake Waikaremoana (Fig. [illegible]; Newnham et al. 1998a), and anal. (*16*) which is from Lake Rotomanuka (Waikato region; Lowe 1988b); anal. (*11b*) is from the initial Kaipo section of Lowe & Hogg (1986). Anal. (*6a*) and (*6b*) are from upper and lower parts of Waiohau Tephra respectively, and (*6c*) is these data combined. Analysis (*19b*) is a trachyandesitic subpopulation within Konini Tephra. Poronui Tephra additionally contained one dacitic shard, and Okupata and Unit-K Tephras each contained one Okataina-derived rhyolitic shard (not reported).

[c] Total Fe as FeO.

[d] Difference between original analytical total and 100.

mineralogical assemblages typical of Taupo-derived Holocene eruptives (Froggatt & Lowe 1990). Constituent glass shard analyses (anal. 8–14, Table 2) are all rhyolitic and compositionally closely matched with those characteristic of a Taupo source and with named correlatives (Lowe 1988a, b; Stokes & Lowe 1988; Froggatt & Rogers 1990; Stokes et al. 1992; Alloway et al. 1994; Shane & Froggatt 1994; Newnham et al. 1995a, 1998a; Eden & Froggatt 1996). Ranges for selected oxides (mean values) are SiO_2 74.9–76.5%, TiO_2 0.2–0.3%, FeO_{total} 1.7–2.1%, MgO 0.2–0.3%, and CaO 1.4–1.6%.

Maroa-derived tephra

This is provisionally referred to as Puketarata Tephra following Froggatt & Lowe (1990). Its identification at Kaipo Bog is based on the predominance of biotite in its ferromagnesian mineralogical assemblage (Topping & Kohn 1973; Froggatt & Lowe 1990; Brooker et al. 1993) and its unusual glass shard composition (anal. 15, Table 2). The very low TiO_2 and MgO concentrations (both <0.1%) correspond to similarly low levels in rhyolitic glass from a possible distal correlative at Lake Rotomanuka in the Waikato region (anal. 16), in glass from near-source Puketarata Tephra, and with analyses on residual glass of lava from Puketarata dome (Ewart et al. 1968; Lowe 1988b). The relatively high K_2O levels (>4%) are similarly distinctive (Lowe 1988a; Stokes & Lowe 1988). Initially, we provisionally identified this tephra layer at Kaipo as the Okataina-derived Rotorua Tephra because of its stratigraphic position between Waiohau and Rerewhakaaitu Tephras, and because the upper part of Rotorua Tephra may contain considerable biotite (Froggatt & Lowe 1990). However, the glass composition does not accord with that previously published for Rotorua Tephra (Green & Lowe 1985; Lowe 1988a, b; Stokes et al. 1992). Rotorua Tephra is distinctive because, paradoxically, its glass is compositionally similar to that of Holocene eruptives from Taupo (rather than Okataina) volcano. In making our correlation with Puketarata Tephra, we assume that all glass throughout the Rotorua eruptive sequence is uniformly "Taupo-like" in composition.

The stratigraphic relationship of Puketarata Tephra to certain other tephras is unclear (cf. Vucetich & Pullar 1973; Topping & Kohn 1973; Lowe 1988b), and it has had limited chronostratigraphic value. Lowe (1988b) suggested, from its occurrence as a composite, disseminated deposit between Rotoaira (which underlies Rotorua Tephra) and Rerewhakaaitu Tephras at Lake Rotomanuka, that it was erupted c. 14 000 ^{14}C yr BP. However, we obtain here an age for "Puketarata Tephra" at Kaipo Bog of c. 13 100 ^{14}C yr BP (see below). This indicates that either the previous age estimate from Lake Rotomanuka was too old or that perhaps two tephras, of identical glass composition, were erupted c. 1000 yr apart from the Puketarata craters of the Maroa Volcanic Centre (i.e., one at c. 14 000 and another at c. 13 100 ^{14}C yr BP).

Tuhua-derived tephra

This is referred to as Tuhua Tephra following the nomenclature of Hogg & McCraw (1983) and Froggatt & Lowe (1990). It has a unique ferromagnesian mineralogical assemblage dominated by sodic phases, especially aegirine (Table 1), and a distinctive peralkaline (molar $[Na_2O + K_2O]/Al_2O_3 > 1$) major element composition (anal. 17, Table 2), consistent with previous mineralogical and glass compositional analyses of this tephra (Lowe 1988a, b; Stokes & Lowe 1988; Froggatt & Lowe 1990; Newnham & Lowe 1991; Pillans & Wright 1992; Newnham et al. 1995b). The glass, although silicic, has relatively low amounts of Al_2O_3 (9.5%) and CaO (0.3%) but characteristically high amounts of FeO_{total} (5.5%) and Na_2O (5.3%).

Tongariro-derived tephra

This tephra was previously identified by Lowe & Hogg (1986) at Kaipo as an unnamed member of the Okupata Tephra Formation of Topping (1973); and Lowe (1988b) implied correlation with the informally named Tongariro-derived "Okupata-1" tephra layer in the Waikato region. The tephra at Kaipo Bog is provisionally correlated here with Okupata Member of Taurewa Formation, newly defined by Donoghue et al. (1999). The Mt Ruapehu-derived Taurewa Formation comprises two members: Okupata Member (tephra-fall deposits) and Pourahu Member (pyroclastic-flow deposits) (Donoghue et al. 1995a, b, 1999). At Kaipo, the tephra contains orthopyroxene and clinopyroxene (Table 1), an assemblage typical of many Tongariro-derived eruptives (Lowe 1988a, b; Froggatt & Rogers 1990; Cronin et al. 1996; Donoghue & Neall 1996; Donoghue et al. 1991, 1995a, 1997, 1999; Nakagawa et al. 1998). The dacitic glass (SiO_2 68.8%) (anal. 18, Table 2) is compositionally consistent with a source in Tongariro Volcanic Centre and generally matches analyses on Okupata Member glass reported by Donoghue et al. (1999) (cf. microprobe analyses of "coarse ash" sample, Hydro Access Rd-10 section; Donaghue et al. 1999). Proportions of Al_2O_3 (15.6%), TiO_2 (0.8%), FeO_{total} (3.4%), MgO (0.9%), and CaO (3.4%) are characteristically high; the moderate K_2O (3%) content helps to exclude the glass from an Egmont source (Lowe 1988a, b; Stokes & Lowe 1988).

Egmont-derived tephra

This tephra is considered to be a correlative of Konini Tephra as defined by Alloway et al. (1995). It is also correlated with the informal unit "Egmont-11" of Lowe (1988b), which underlies "Okupata-1" in the Waikato region. The tephra layer at Kaipo has a ferromagnesian mineralogy dominated by hornblende and clinopyroxene with lesser amounts of orthopyroxene (Table 1), typical of many Egmont-derived eruptives (Kohn & Neall 1973; Lowe 1988b; Price et al. 1999). The very fine grained texture of the deposit is consistent with it being transported a relatively long distance—Kaipo Bog is c. 300 km from Mt Egmont (Taranaki). The trachydacitic glass composition (anal. 19a, Table 2) supports an Egmont affinity (e.g., Lowe 1988a, b; Stokes & Lowe 1988; Pillans & Wright 1992; Eden & Froggatt 1996; Price et al. 1999), especially the high K_2O content (4.2%). The glass is relatively high in TiO_2 (0.7%), Al_2O_3 (17.4%), FeO_{total} (3.3%), MgO (1.0%), and Na_2O (5.0%).

The subpopulation of low-K_2O, trachyandesitic glass (anal. 19b, Table 2) in the Konini Tephra layer has uncertain origin. The shards may be derived from the Tongariro Volcanic Centre, suggesting that there has been admixing between deposits from closely spaced eruptions (Lowe 1988a). Alternatively, they may represent a less-differentiated magmatic fraction associated with the Konini or other eruption at Egmont (e.g., see Shane in press).

CHRONOLOGY

Twenty-three radiocarbon dates have been obtained from the Kaipo sequence: 15 dates were reported by Lowe & Hogg (1986) and 8 further dates are reported here (Fig. 2; Table 3). All but one of the dates were assayed by the University of Waikato Radiocarbon Dating Laboratory (prefixed Wk) using conventional liquid scintillation spectometry; the Rafter (New Zealand) Radiocarbon Laboratory undertook the analysis of one sample (NZA7751) using accelerator mass spectrometry. The ages, corrected for isotopic fractionation, are reported in conventional radiocarbon years (^{14}C yr) BP.

The ages progressively increase in age down the section with no stratigraphic inversions from tephra to tephra, and thus very little mixing or contamination has occurred in the sequence. Coarse and fine peat fractions are demonstrably contemporaneous (Lowe & Hogg 1986) and duplicate samples accord closely with one another (Table 3). Only three samples, Wk493–495, are considered unreliable and hence omitted from further consideration. Our revised stratigraphy shows that these three samples, originally reported by Lowe & Hogg (1986) as being "too young" with respect to the age assigned to the underlying Rotoma Tephra, came from a part of the section that had been locally truncated.

In addition to the ages obtained by radiocarbon dating, the 16 tephra layers provide a further set of independent ages for the Kaipo sequence because all but two of them have been dated elsewhere, many with numerous associated

Table 3 Radiocarbon ages from Kaipo Bog, listed stratigraphically.

Lab. No.[a]	Age (^{14}C yr BP)[b]	$\delta^{13}C$ (‰)	Sample type[c] (thickness, mm)	Stratigraphic position (see Fig. 2)	Comment (reference)[d]
Wk499	2910 ± 60	–25.7	P-r (20)	Overlies Waimihia Tephra (S1)[e]	(1, 2)
Wk500	3040 ± 50	–26.4	P-f (20)	Overlies Waimihia Tephra (S1)	Same sample as Wk499 (1, 2)
Wk498	3250 ± 70	–26.4	P-b (20)	Underlies Waimihia Tephra (S1)	(1, 2)
Wk496	4490 ± 60	–26.9	P-b (20)	Underlies Unit-K ("Hinemaiaia")	(1, 2)
Wk497	4530 ± 60	–26.4	P-b (20)	Underlies Unit-K ("Hinemaiaia")	Same sampling position as Wk496 (duplicate) (1, 2)
Wk501	4860 ± 70	–26.4	P-b (20)	Underlies Whakatane Tephra	(1, 2)
Wk4413	7380 ± 70	–26.4	P-b (20)	Underlies Mamaku Tephra	(3)
(Wk493)[f]	5440 ± 170	–25.8	P-r (20)	Overlies Rotoma Tephra	Unreliable with respect to Rotoma Tephra (1, 2)
(Wk494)[f]	7380 ± 80	–26.8	P-f (20)	Overlies Rotoma Tephra	Same sample as Wk493, unreliable with respect to Rotoma Tephra (1, 2
(Wk495)[f]	7560 ± 100	–26.2	P-b (20)	Overlies Rotoma Tephra	Same sampling position as Wk494 (duplicate), unreliable with respect to Rotoma Tephra (1, 2)
Wk492	8710 ± 80	–26.7	P-b (20)	Overlies Opepe Tephra (E)	(1, 2)
Wk491	9560 ± 80	–27.0	P-b (20)	Overlies Poronui Tephra (C)	(1, 2)
Wk352	9960 ± 90	–28.5	P-f (20)	Underlies Poronui Tephra (C)	(1, 2)
Wk351	10160 ± 130	–29.4	P-r (20)	Underlies Poronui Tephra (C)	Same sample as Wk352 (1, 2)
NZA7761	10146 ± 76	–29.1	P-b (40)	Underlies Konini Tephra	AMS date – dual lab. no. Wk5404[g] (3)
Wk263	10600 ± 90	–29.6	P-b (20)	Basal peat overlying pale brownish-grey mud unit	Equivalent stratigraphic position to Wk5162 (1, 2)
Wk5162	10790 ± 70	–30.0	P-b (30)	Basal peat overlying pale brownish-grey mud unit	(3)
Wk5164	11360 ± 210	–31.8	M-p (40)	Dark brown peaty mud layer "B"	(3)
Wk264	11500 ± 80	–29.1	M-p (20)	Dark brown peaty mud layer "A"	(1, 2)
Wk5403	12180 ± 260	–31.1	M-sp (40)	Base of pale brownish-grey mud unit overlying Waiohau Tephra	(3)
Wk4414	12420 ± 90	–28.4	P-b (30)	Underlies Waiohau Tephra	(3)
Wk5163	13420 ± 80	–31.2	M-p (40)	Base of peat transitional to basal olive-blue sandy mud unit	(3)
Wk5165	14700 ± 160	–30.5	M-p (30)	Overlies Rerewhakaaitu Tephra	(3)

[a]Wk, University of Waikato Radiocarbon Dating Laboratory number; NZ, Rafter (New Zealand) Radiocarbon Dating Laboratory number.

[b]Conventional radiocarbon years BP based on the old (Libby) half-life ± 1 SD from counting statistics. Errors for dates referenced (3) are multiplied by laboratory error multiplier (K) of 1.217. $\delta^{13}C$ measurements are ± 0.2‰.

[c]P-b, bulk peat; P-r, roots (>c. 1 mm diameter) extracted from bulk peat; P-f, fine peat residual from bulk peat after root extraction; M-p, peaty mud; M-sp, slightly peaty mud. All samples were washed in hot 10% HCl, rinsed and dried prior to assay.

[d]References: 1, Lowe & Hogg (1986); 2, Hogg et al. (1987); 3, this study.

[e]Alternative tephra names given in parentheses (see text, Table 1).

[f]Ages are unreliable with respect to eruption of Rotoma Tephra (too young) but consistent with a hiatus in the stratigraphy of the original section sampled by Lowe & Hogg (1986) in which Tuhua and Mamaku Tephras were missing from the zone between Whakatane and Rotoma Tephras.

[g]Sample CO_2 prepared by Waikato laboratory, assayed using AMS by Rafter laboratory (both laboratory numbers apply).

dates. Ages assigned to the tephras are summarised in Fig. 2 and Table 1, and are discussed below, from youngest to oldest. We include also in this section provisional "mid-range" estimates (2-sigma level) of the calendar age (cal yr BP) for each tephra, based on OxCal (Bronk Ramsey 1995). These estimates, derived from the terrestrial calibration curves of Stuiver et al. (1998), are necessarily approximate because of multiple intercepts, errors on both ages and curves, and other factors (Stuiver & van der Plicht 1998). Some of the calibrated ages span hundreds of years in range. Corrections for the interhemispheric offset (McCormac et al. 1998) were applied to the estimates for Kaharoa and Taupo Tephras only.

Tephra ages

Kaharoa Tephra is aged 665 ± 15 ^{14}C yr BP, the error-weighted mean (EM) age obtained from cluster analysis of 22 radiocarbon ages minus 8 statistical outliers (Lowe et al. 1998). The calibrated age is c. 600 cal yr BP (c. AD 1350) (Lowe et al. 1998).

Taupo Tephra (Subunit-Y5) has an EM age (n = 41) of 1850 ± 10 ^{14}C yr BP (Froggatt & Lowe 1990), consistent with an EM age (n = 7) obtained on short-lived leaves and seeds of 1845 ± 19 ^{14}C yr BP (Lowe & de Lange in press). The calibrated age is c. 1750 cal yr BP (c. AD 200) (Lowe & de Lange in press). Other possible calendar dates for Taupo Tephra are AD 186 (based on interpretations of historical records; Wilson et al. 1980), AD 181 ± 2 (from ice-core records; Zielinksi et al. 1994), c. AD 177 (1-sigma range AD 166–195) (from dendrochronology; Froggatt & Lowe 1990), and AD 232 ± 15 (from dendrochronology; Sparks et al. 1995).

Waimihia Tephra (Subunit-S1) has an EM age (n = 17) of 3230 ± 20 ^{14}C yr BP. We calculated this by re-evaluating the 17 ages reported for Waimihia Tephra by Froggatt & Lowe (1990), three of which are now known to relate to the older Stent tephra (Alloway et al. 1994). Two new ages obtained by Wilson (1993) on charcoal and one by Holdaway & Beavan (1999) on moa eggshell were included in the determination of the mean: 3340 ± 50 ^{14}C yr BP (Wk1840), 3290 ± 50 ^{14}C yr BP (Wk1841), and 3005 ± 68 ^{14}C yr BP (NZA7701). Three ages (Wk498, 499, 500) obtained by Lowe & Hogg (1986) from samples associated with Waimihia Tephra at the original Kaipo section support our adopted age (Fig. 2). The calibrated age is c. 3450 cal yr BP.

Unit-K, the most voluminous and widely dispersed of the previously so-called "Hinemaiaia" units (Wilson 1993), has an EM age (n = 13) of 4510 ± 20 ^{14}C yr BP. This age is based on a re-evaluation of the 12 ages used by Froggatt & Lowe (1990) (two ages were discarded as outliers, NZ3160, 3161) together with a new age on charcoal, 4630 ± 200 ^{14}C yr BP (Wk1835), reported by Wilson (1993), and two on peat, 4330 ± 80 ^{14}C yr BP (Wk1495) and 4600 ± 70 ^{14}C yr BP (Wk2152), reported by Alloway et al. (1994) and Newnham et al. (1995a). It is consistent with two ages (Wk496, 497) obtained by Lowe & Hogg (1986) at Kaipo for this tephra. The calibrated age is c. 5200 cal yr BP.

Whakatane Tephra has an EM age (n = 21) of 4830 ± 20 ^{14}C yr BP (Froggatt & Lowe 1990), in close agreement with the age (Wk501) obtained at Kaipo by Lowe & Hogg (1986). It has a calibrated age of c. 5550 cal yr BP.

Tuhua Tephra has an EM age (n = 10) of 6130 ± 30 ^{14}C yr BP (Froggatt & Lowe 1990), equivalent to a calibrated age of c. 7000 cal yr BP.

Mamaku Tephra has an EM age (n = 22) of 7250 ± 20 ^{14}C yr BP (Froggatt & Lowe 1990), which is close to the age of 7380 ± 70 ^{14}C yr BP (Wk4413) obtained on peat below this tephra (Fig. 2). The calibrated age is c. 8050 cal yr BP.

Rotoma Tephra has an EM age (n = 45) of 8530 ± 10 ^{14}C yr BP (Froggatt & Lowe 1990), equivalent to a calibrated age of c. 9500 cal yr BP.

Opepe Tephra (Unit-E) has an EM age (n = 10) of 9050 ± 40 ^{14}C yr BP (Froggatt & Lowe 1990), which was adopted also by Wilson (1993). It is consistent with the age (Wk492) obtained on this tephra at Kaipo by Lowe & Hogg (1986). The calibrated age is c. 10 200 cal yr BP.

Poronui Tephra (Unit-C) has an EM age (n = 3) of 9840 ± 60 ^{14}C yr BP (recalculated from Froggatt & Lowe 1990). It is derived from the three ages (Wk491, 351, 352) obtained by Lowe & Hogg (1986) at Kaipo for this tephra. Wilson (1993) adopted an age of 9800 ^{14}C yr BP for Poronui Tephra/Unit-C. The calibrated age is c. 11 350 cal yr BP.

Karapiti Tephra (Unit-B) has an EM age (n = 4) of 9820 ± 80 ^{14}C yr BP (Froggatt & Lowe 1990). At face value there is no time difference between this age and that adopted for Poronui Tephra. However, the accumulation of peat between the two tephras at Kaipo and the development of a (weak) paleosol on Karapiti Tephra/Unit-B near the source (Wilson 1993) indicate that some time must have elapsed between the Karapiti and Poronui eruptions. Consequently, we adopt here an EM age (n = 2) of 10 030 ± 90 ^{14}C yr BP for Karapiti Tephra, which is based on two charcoal-derived ages, 9910 ± 130 ^{14}C yr BP (NZ4847) and 10 150 ± 130 ^{14}C yr BP (Wk1846), as used by Wilson (1993). (The EM age derived from pooling all available ages (n = 5) is 9910 ± 70 ^{14}C yr BP.) The adopted age has an equivalent calibrated age of c. 11 700 cal yr BP.

Okupata Member (of Taurewa Formation) is here assigned an age of c. 10 100 ^{14}C yr BP, which we estimated from rates of sedimentation at Kaipo (Fig. 3). Although no direct dates are available for this tephra near its source, it is constrained chronostratigraphically by Karapiti and Waiohau Tephras to between c. 10 000 and 11 850 ^{14}C yr BP (Donoghue et al. 1995b, 1999). Its likely distal correlative in the Waikato region, "Okupata-1", was assigned an age of c. 10 100 ^{14}C yr BP based on a series of dates on stratigraphically adjacent deposits in Lake Maratoto (Hogg et al. 1987; Lowe 1988b). These dates included 10 000 ± 120 ^{14}C yr BP (Wk232) and 10 120 ± 100 ^{14}C yr BP (Wk213) from tephras just above "Okupata-1", and 10 100 ± 100 ^{14}C yr BP (Wk519) on "Egmont-11" (i.e., Konini Tephra) just below it (Lowe 1988b). The calibrated age is estimated at c. 11 750 cal yr BP.

Konini Tephra has an EM age (n = 4) of 10 150 ± 50 ^{14}C yr BP. This is based on two ages obtained on Konini Tephra in

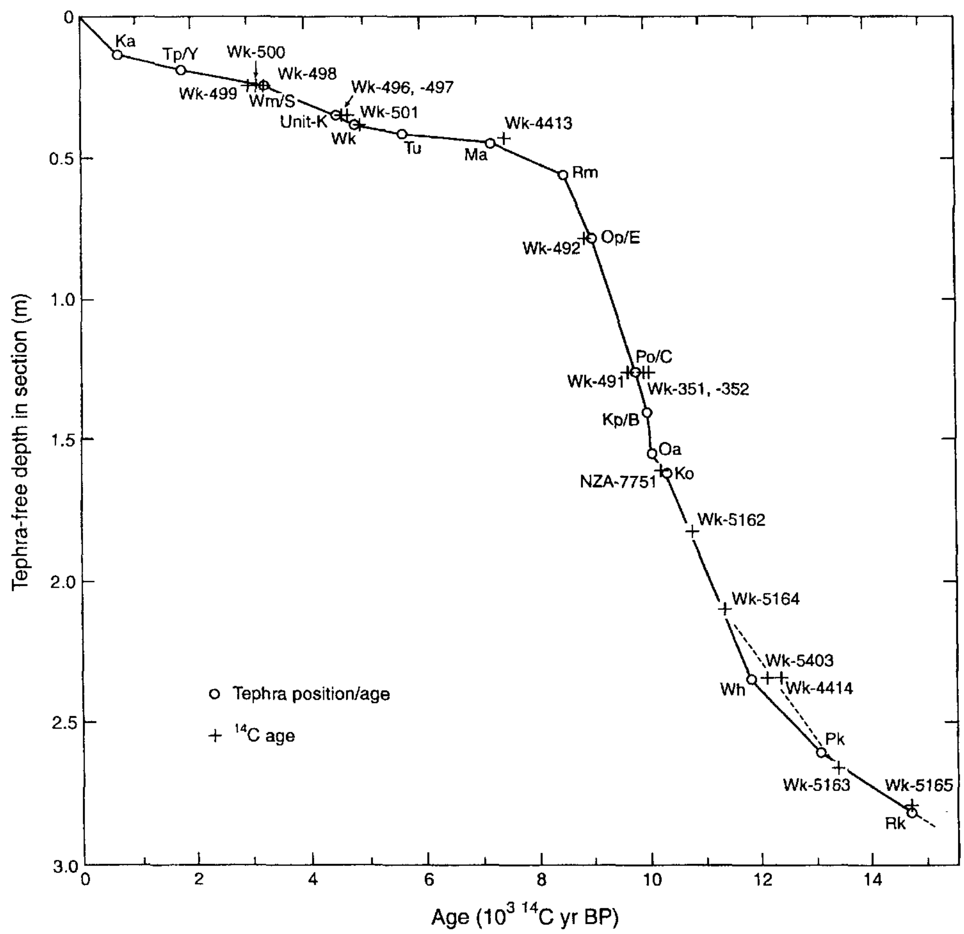

Fig. 3 Sediment age-depth curve for the Kaipo Bog sequence. Abbreviations for tephras are given in Table 1. The solid curve is drawn through the tephra-age data points and Wk5163; the dashed curve is drawn through the mid-point of Wk5403 and Wk4414. The ^{14}C-based age points (+) are closely aligned to the tephra-age based curve.

the Taranaki region of 10 150 ± 100 ^{14}C yr BP (NZ3153) and 10 450 ± 200 ^{14}C yr BP (NZ5410) (Alloway et al. 1995), and one on its likely correlative, "Egmont-11", in the Waikato region of 10 100 ± 100 ^{14}C yr BP (Wk519) (Lowe 1988b). We obtained a corroborative age (NZA7751) on this tephra at the Kaipo section of 10 146 ± 76 ^{14}C yr BP (Fig. 2), and this was included in the mean age calculation. The calibrated age is c. 11 850 cal yr BP.

The four tephra layers just discussed—Poronui, Karapiti, Okupata, and Konini—are individually not able to be separated on the basis of radiocarbon age alone, probably in part because they fall within one of the "radiocarbon plateau" episodes that occurs at c. 10 000 ^{14}C yr BP (Ammann & Lotter 1989; Björck et al. 1998; Stuiver et al. 1998). However, we have been able to apply reasonable age estimates to these tephras at Kaipo because they occur in stratigraphic succession with peat deposited between them, so that the lowermost tephra is clearly older than the uppermost one by possibly some hundreds of years. The ages we have assigned to these tephras are further constrained by the dates newly obtained on the underlying pale brownish-grey muds (Wk5162, 5164), which are themselves supported by previous dates from this part of the sequence (Wk263, 264) as reported by Lowe & Hogg (1986) (Fig. 2).

Waiohau Tephra has an EM age ($n = 12$) of 11 850 ± 60 ^{14}C yr BP based on Froggatt & Lowe's (1990) analysis. Subsequent statistical analyses of all available ages on Waiohau Tephra generated mean ages that do not differ significantly from this age (T. F. G. Higham pers. comm. 1998). The age of 11 850 ± 60 ^{14}C yr BP is a little younger than the two new ages of 12 180 ± 260 ^{14}C yr BP (Wk5403) and 12 420 ± 90 ^{14}C yr BP (Wk4414) returned on samples from above and below Waiohau Tephra, respectively (Fig. [illegible]). It is possible that these new ages contain a component of older carbon derived from catchment inwashing during a period of instability at around the time of deposition of Waiohau Tephra (cf. Yoshikawa et al. 1988; McGlone 199[illegible]), and hence may overestimate the age of the tephra by several hundred years. Evidence for such inwashing, hence probable "old" carbon contamination, includes the overthickening (reworking) of the upper part of the Waiohau Tephra, the lithological change from peat to mud following its deposition, and the relatively high proportion of degraded pollen grains in samples taken from immediately above it (Newnham & Lowe in prep.). The calibrated age for Waiohau Tephra is c. 13 800 cal yr BP.

Puketarata Tephra has not previously been dated directly but an age of c. 14 000 ^{14}C yr BP was obtained by Lowe (1988b) from micro-tephra analysis in the Waikato region. This estimate clearly is incompatible with the age of 13 4[illegible]0 ± 80 ^{14}C yr BP (Wk5163) obtained from a slice of peat 4[illegible]–80 mm below the base of "Puketarata Tephra" as identified at Kaipo Bog (Fig. 2). We have estimated an age of c. 13 1[illegible]0 ^{14}C yr BP for the Puketarata Tephra layer at Kaipo using sedimentation rates constrained by the Wk5163 and Waiohau

Tephra (11 850 ^{14}C yr BP) datums (Fig. 3). The calibrated age here is c. 15 800 cal yr BP.

Rerewhakaaitu Tephra has an EM age (n = 3) of 14 700 ± 110 ^{14}C yr BP (from Froggatt & Lowe 1990), which is identical to the age (Wk5165) of 14 700 ± 160 ^{14}C yr BP obtained on peaty mud immediately overlying this tephra (Fig. 2). Including Wk5165 in the calculation gives an EM age (n = 4) of 14 700 ± 95 ^{14}C yr BP, which we adopt here. The calibrated age is c. 17 700 cal BP.

The base of the sequence, a few centimetres below Rerewhakaaitu Tephra, is likely to be close to c. 15 000 ^{14}C yr BP in age, equivalent to c. 18 000 cal yr BP.

Radiocarbon versus tephrochronological ages

We have constructed a sediment age-depth curve for the Kaipo sequence (Fig. 3). It demonstrates clearly that the radiocarbon ages obtained at Kaipo are closely aligned to the tephra-age curve derived from tephrochronology, as discussed above. Thirty-four radiocarbon dates, 20 on peats and 14 mean ages associated with the tephra layers, have been applied to the Kaipo sequence. These 14 tephra-based dates are derived, in turn, from some 250 radiocarbon dates on the tephras in environments elsewhere (e.g., Hogg et al. 1987; Froggatt & Lowe 1990; Wilson 1993), that is, around 270 dates have, in effect, been brought to bear on the Kaipo sequence. The 34 radiocarbon dates applied to the sequence represent an average of one date every c. 80 mm of sediment (excluding tephra deposits), equivalent to c. 430 yr of sedimentation.

Sedimentation rates and implications for lateglacial paleoenvironments

The average sedimentation rate (on a tephra-free basis and using radiocarbon years) for the entire Kaipo sequence is 0.19 mm/yr, comparable with similar rates for a bog at Holdens Bay, Rotorua (McGlone 1983) and peat lakes in the lowland Waikato region (Lowe 1988b; Newnham et al. 1989) (see also Froggatt & Rogers 1990), but considerably slower than mean rates of c. 1 mm/yr at Rukuhia and Kopouatai Bogs in the Waikato region (Green & Lowe 1985; Newnham et al. 1995b) and at Lake Poukawa, Hawke's Bay (Howorth et al. 1980). However, the rates of accumulation at Kaipo have varied with three distinct phases evident (Fig. 3): relatively slow (0.17 mm/yr) before c. 12 000 ^{14}C yr BP (marked by Waiohau Tephra); relatively fast (0.52 mm/yr) from c. 12 000 to 8500 ^{14}C yr BP; and very slow (0.07 mm/yr) after 8500 ^{14}C yr BP (marked by Rotoma Tephra). (Rates in calendar years are c. 0.12, 0.42, and 0.06 mm/cal yr, respectively.) This pattern may relate broadly to climatic change (cf. McGlone & Topping 1977; Green & Lowe 1985; Hogg et al. 1987). Newnham & Lowe (in press) suggested that the general "tripartite" sequence at Kaipo, comprising lower and upper peat deposits with intervening brownish-grey muds, and the associated variations in sedimentation rates, resemble many "classic" sedimentary sequences from the North Atlantic margins where Younger Dryas cooling (between c. 11 000 and 10 000 ^{14}C yr BP) is best expressed (Björck et al. 1998; Björck & Wastegård 1999). Waiohau Tephra was identified by Newnham & Lowe (in press) as an especially important chronostratigraphic datum in the sequence because it marks the base of the brownish-grey mud unit and the change in sedimentation rates that may represent a cooling signal.

DISCUSSION AND CONCLUSIONS

We have documented here the stratigraphic interrelationships, composition, and chronology of a succession of 16 distal, silicic tephra layers interbedded with peats and muds at the montane Kaipo Bog, Huiarau Range, eastern North Island. The base of the sediments is dated at c. 15 000 ^{14}C yr BP (c. 18 000 cal yr BP). Aged from 665 ± 15 to 14 700 ± 95 ^{14}C yr BP, the tephras are derived from six different volcanic centres in North Island, three of which are rhyolitic (Okataina, Taupo, Maroa), one peralkaline (Tuhua), and two andesitic (Tongariro, Egmont). Correlations, based on multiple criteria, are necessarily provisional in some cases because of current ambiguities or limitations in relevant data.

Six of the tephras have not been recorded previously at the Kaipo site: Tuhua, Mamaku, Konini, Waiohau, Puketarata, and Rerewhakaaitu. Four of these (Tuhua, Mamaku, Konini, Puketarata) have not been recorded in eastern North Island, and so their occurrence at Kaipo Bog greatly extends their known distribution (Pullar & Birrell 1973; Lowe 1988b; Froggatt & Lowe 1990). It is likely that further microscopic or "cryptic" tephra layers (Hunt & Lowe in prep.), not visible as macroscopic layers, will be present at Kaipo because such deposits have been recorded at Lake Tutira, c. 65 km to the south near Napier, and at Lake Repongaere, c. 60 km to the east near Gisborne (Fig. 1; Eden et al. 1993; Eden & Froggatt 1996; Wilmshurst et al. 1999).

Some important tephra markers

The identification of Rerewhakaaitu Tephra at Kaipo Bog, and confirmation of its age at 14 700 ± 95 ^{14}C yr BP, provides further scope for its application as a critical marker bed at the end of the last cold stage in both terrestrial and marine environments (e.g., Stewart & Neall 1984; Newnham et al. 1989; Carter et al. 1995).

The tephra identified at Kaipo as Puketarata Tephra and dated at c. 13 100 ^{14}C yr BP is identical in composition to a Maroa-derived distal micro-tephra in the Waikato region dated at c. 14 000 ^{14}C yr BP (Lowe 1988b). These deposits may be correlatives (in which case the Waikato estimated age is apparently too old) or they may be separate tephras erupted c. 1000 ^{14}C years apart but with a common source, presumably from vents in the Puketarata craters area (Brooker et al. 1993). In any event, the occurrence of the distinctive c. 13 100 ^{14}C yr BP tephra at Kaipo is noteworthy because it is well beyond previously mapped limits (Lloyd 1972; Brooker et al. 1993) and it is potentially a useful chronostratigraphic marker bed.

Waiohau Tephra (11 850 ± 60 ^{14}C yr BP) provides a critical chronostratigraphic marker at Kaipo, analagous to widespread tephras of similar age elsewhere that are used to correlate and date signals of lateglacial climatic change. Such tephras include the Laacher See, Vedde, Borrobol, and Ravel in northwest Europe (e.g., Bogaard & Schminke 1985; Juvigné et al. 1992; Turney et al. 1997; Bauer et al. 1999; Björck & Wastegård 1999), Glacier Peak tephra in North America (e.g., Busacca et al. 1992), the "Volcan Réclus" tephra in South America (McCulloch & Bentley 1998), and the Towada-H and Ulreung Oki tephras in and around Japan (Machida 1999).

The Egmont-derived Konini Tephra, now well dated at 10 150 ± 50 ^{14}C yr BP and identified in Taranaki, Waikato, and eastern North Island regions, forms a widespread marker bed for lateglacial–early Holocene conditions.

If our provisonal correlations are confirmed, then the occurrence of the Mt Ruapehu derived, c. 10 100 ^{14}C yr BP Okupata Member of Taurewa Formation at well-separated sites in eastern North Island and the Waikato region is consistent with deposition from a substantial plinian eruption. This supports the conclusions of Donoghue et al. (1999) who showed the Taurewa Eruptive Episode to be the largest known from Mt Ruapehu since c. 22 600 ^{14}C yr BP. The Okupata Member has an estimated total volume of at least 0.23 km^3 (Donoghue et al. 1999).

Tuhua Tephra (6130 ± 30 ^{14}C yr BP), previously identified in the Auckland and Waikato regions northwest and southwest, respectively, of the source volcano at Mayor Island (Fig. 1; Lowe 1988b; Newnham & Lowe 1991), was clearly distributed in a southeasterly direction as well (see also Kennedy & Froggatt 1984). With its distinctive composition, Tuhua Tephra forms an important regional marker of mid-Holocene age (Newnham et al. 1995b).

The Taupo (1850 ± 10 ^{14}C yr BP) and Kaharoa (665 ± 15 ^{14}C yr BP) Tephras, both identified at Kaipo Bog, are well established late Holocene marker beds in North Island. Kaharoa Tephra is essentially coincident with the earliest environmental impacts of Polynesian settlement (Lowe et al. 1998, in press; Newnham et al. 1998b; Wilmshurst et al. 1999).

Glass composition

The new major element compositional analyses on glass shards from each of the tephra layers, obtained by electron microprobe (Table 2), are valuable additions to the glass geochemical database being developed for New Zealand tephra layers, and thereby add to their potential usefulness as isochronous stratigraphic markers. Such analyses, especially those on the tephras from non-rhyolitic sources, which are sparse, are usually the most useful means of matching tephra layers to source volcanoes and, in many cases, to specific named eruptives (e.g., Froggatt 1983; Stokes et al. 1992; Dugmore et al. 1995; Pilcher et al. 1996; Shane et al. 1996; Cronin et al. 1997; Turney et al. 1997; Lowe & Newnham 1999; Shane in press).

Paleoenvironmental applications

Establishing a sound chronology for the Kaipo peat sequence is an essential first step towards undertaking detailed, fine-resolution paleoenvironmental studies at this climatically sensitive site (Newnham & Lowe in press, in prep.). Ultimately, the chrono-tephrostratigraphy reported here will underpin attempts to correlate short-term regional or global paleoclimatic changes for the lateglacial and Holocene periods, and especially to determine the degree of synchrony of such changes between Northern and Southern Hemispheres, including the Younger Dryas chron (e.g., Lowell et al. 1995; Björck et al. 1996; Newnham & Lowe in prep.). The chronostratigraphic framework that we have established for the Kaipo sequence is based on 34 reliable ages comprising 20 site-specific radiocarbon ages together with 14 mean ages on the tephra layers, which were derived from other North Island sites using tephrochronology. The site-specific radiocarbon ages and the independently derived tephra-based ages show close accordance, indicating that the sequence is soundly dated.

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