Stratigraphy, age, composition, and correlation of late Quaternary tephras interbedded with organic sediments in Waikato lakes, North Island, New Zealand

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Abstract Cores from 14 peaty lakes in the central Waikato region, northern North Island, contain a sequence of 41 well-preserved, mainly macroscopic, occasionally bedded, ash and lapilli layers ranging in thickness from c. 2 to 110 mm and interbedded with fine-grained organic lake sediment. The layers, whose field and compositional properties are described in detail, are distal airfall tephras that were erupted between c. 17 000 and c. 1800 ^{14}C years ago from six rhyolitic and andesitic volcanic centres located c. 70–200 km from the Waikato sites: Taupo (5 tephras), Okataina (7), Maroa (1) (rhyolitic); Mayor Island (2) (peralkaline); Tongariro (11), and Egmont (15) (andesitic).

These sources were distinguished using the tephras' mineralogical assemblages and glass and mineral compositions (determined by electron microprobe). The tephras were correlated with named proximal eruptives using their stratigraphic relationships and radiometric ages (based on multiple ^{14}C dates on enclosing lake sediment) in combination with the mineralogical and chemical criteria. The correlated tephras associated with each source (listed youngest to oldest) are: *Taupo*—Taupo, Mapara, Whakaipo, Hinemaiaia, Opepe; *Okataina*—Whakatane, Mamaku, Rotoma, Waiohau, Rotorua, Rerewhakaaitu, Okareka; *Maroa*—Puketarata; *Mayor Island*—Tuhua, uncorrelated; *Tongariro*—Mangamate (?Te Rato Lapilli), Okupata (8 informal units Oa-1 to Oa-8), uncorrelated, Rotoaira; and *Egmont*—15 informal units Eg-1 to Eg-15.

In total, the post c. 15 000 year lacustrine tephras range in thickness from c. 20 cm (possibly equivalent to c. 37 cm on dry land because of compaction or dissemination in the lakes) in the north of the study area, to c. 25 cm (c. 47 cm on dry land) in the south, to c. 42 cm (c. 78 cm on dry land) in the east. Of these total thicknesses, rhyolitic tephras make up c. 65–95%; andesitic tephras are more common in the south (c. 30–35%), decreasing markedly to the north (c. 10–15%) and east (c. 5%). These different proportions of andesitic to rhyolitic material may have influenced weathering and argillisation in the tephra-derived soils in the Waikato area.

Provisional isopach maps for 11 tephras (Whakaipo, Eg-2, Tuhua, Mamaku, Rotoma, Opepe, Mangamate, Waiohau, Oa-8, Rotorua, and Rerewhakaaitu) are presented. The thickness resolution of these is generally one to two orders of magnitude greater than in most previous isopach maps in New Zealand, and attests to the value of using lake sediments for tephra mapping. Most of the tephras found in the Waikato lakes should persist well beyond the Waikato area. Extrapolated plots of isopach thickness against distance from isopach centre suggest that c. 1 mm isopachs should occur c. 200–300 km from source. Many of the tephras were probably emplaced by powerful eruptions (possibly including directed blasts), or were dispersed by strong winds, or both. Co-ignimbrite ash may have contributed to some of the resulting lacustrine tephra deposits.

The 41 tephras identified in the Waikato lake cores record, on average, an eruptive event every c. 400 years (rhyolitic, 1 per c. 1100 years; andesitic, 1 per c. 650 years). The tephras, particularly Taupo, Tuhua, Mamaku, Opepe, Mangamate, Waiohau, Rotorua, Rerewhakaaitu, and Okareka, are useful as time-stratigraphic markers in paleoenvironmental studies on the lakes and catchments.

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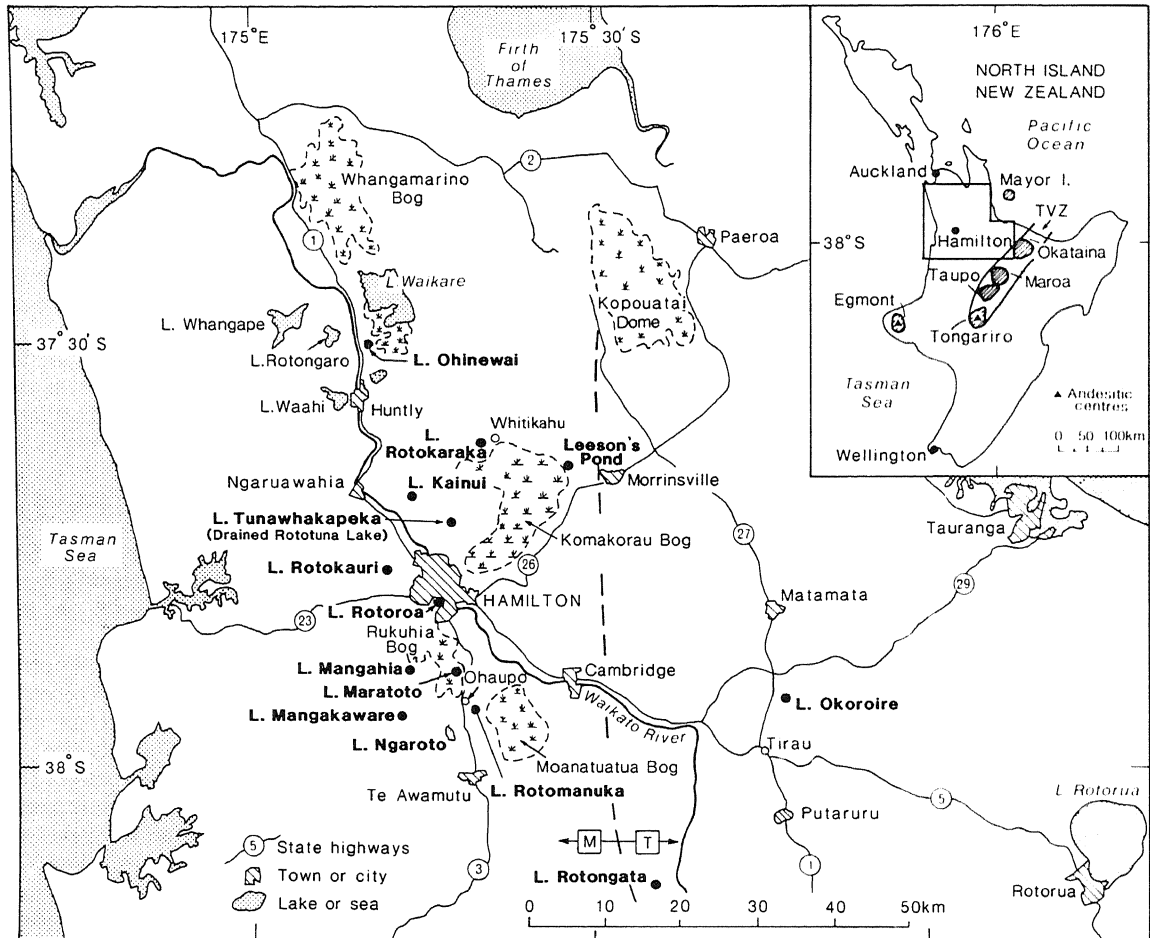
Fig. 1 The Waikato area showing the locations of the lakes cored in this study (bold). Some other lakes and peat bogs are also shown. The dashed line marks the approximate boundary of the two main soil-forming materials described in early soil surveys as "Mairoa Ash" (M) and "Tirau Ash" (T) (after N.Z. Soil Bureau 1954). The inset shows the locations of tephra-producing rhyolitic and andesitic volcanic centres active in the late Quaternary period (after Cole & Nairn 1975 and Hogg & McCraw 1983). TVZ = Taupo Volcanic Zone.

INTRODUCTION

The central Waikato region is well to the north and northwest of the main tephra-producing volcanoes of central North Island (Fig. 1; McCraw 1975). Consequently, most of the late Quaternary airfall tephra deposits found there are relatively thin and have been hard to differentiate. Early reconnaissance mapping of the tephras, chiefly for soil survey purposes, separated two main soil-forming materials which were named Mairoa Ash and Tirau Ash (Grange 1931; Grange & Taylor 1932; Taylor 1933; Grange et al. 1939; N.Z. Soil Bureau 1954). Although each of these deposits was believed to be composed of materials derived from several

eruptions, they were arbitrarily named "Ash", rather than "Ashes" or "Ash Beds", for purposes of soil description and classification (Gibbs et al. 1982). Tirau Ash, considered to be primarily but not wholly rhyolitic, formed the parent material of soils in eastern parts of the Waikato; Mairoa Ash, thought to contain a greater component of andesitic ash beds of an intermittent origin, extended westward from the Tirau Ash boundary to the west coast (Fig. 1). Taupo Pumice was recognised in soil profiles as far north as Putaruru (Grange & Taylor 1932), and as a discrete lapilli layer near the surface of the Rukuhia and Moanatuatua peat bogs (Grange et al. 1939; Tonkin 1967).

More recent studies on stratigraphic sections and soil profiles in the Waikato and adjoining districts (Pullar 1967, 1978; Vucetich & Pullar 1969; Pullar & Birrell 1973a, b; Pullar et al. 1973; Hodder & Wilson 1976; Lowe 1979, 1981a; Orbell 1982; Parfitt et al. 1982a) confirmed the composite nature of the Mairoa Ash and Tirau Ash, and identified some of the tephras making up the deposits at a number of sites. These identifications were achieved either by careful hand-over-hand field methods (e.g., Vucetich & Pullar 1969; Pullar & Birrell 1973b), or by mineralogical and geochemical methods based on laboratory analyses (e.g., Hodder & Wilson 1976; Lowe 1981a; see also Hogg & McCraw 1983).

Both these approaches have limitations, however. The chief difficulties in the field arise from the loss of identifying characteristics as individual tephras thin away from source towards the Waikato area, collapsing into composite beds (Pullar 1967), and from the masking effects of postdepositional erosion, mixing, and weathering in the soil-forming environment. In the laboratory, detailed grain-by-grain "fingerprinting" methods circumvented these problems to some extent, but relatively few tephras were identified with certainty.

An additional complication has been the necessity to consider the proposal that loess contributed significantly to the surficial deposits in some parts of the region (McCraw 1967; Vucetich 1968; Cowie & Milne 1973). However, this proposal was largely discounted by Lowe (1981a).

The obtaining of a 3.2 m long sediment core from Lake Maratoto, a small peaty lake near Ohaupo (Fig. 1), heralded a new approach to elucidating the late Quaternary tephrostratigraphy of the Waikato area. The core contained a succession of multiple, essentially unweathered, discrete tephra layers separated from one another by fine-grained organic lake sediment (Lowe et al. 1980). Most of the tephras, aged ≤c. 15 000 years*, were identified (some tentatively) by their dominant ferromagnesian mineralogy, their stratigraphic position, and by five radiocarbon dates (the first to be obtained on airfall tephras in the Hamilton Basin). Lowe et al. (1980) showed that some of the tephras were derived from Mayor Island, Tongariro, and possibly Mt Egmont sources in addition to Okataina and Taupo Volcanic Centres (Fig. 1,

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*All ages reported and discussed in the text are conventional radiocarbon ages based on the Libby (old) half-life of 5568 years (Hogg et al. 1987).

inset). The core thus revealed that "Mairoa Ash" in the Ohaupo area was likely to comprise many more tephras than had previously been considered present, and that these were derived from a variety of North Island volcanic centres (Lowe 1981b).

Since this first core was taken from Lake Maratoto, a further 13 lakes, and several peat bogs, in the Waikato region have been cored (Fig. 1) to give a wider picture of tephra occurrence and distribution. The initial findings of Lowe et al. (1980) for Lake Maratoto were partly modified (some tephras were re-identified) and further cores examined in more detail by Green & Lowe (1985). Some analyses of cores from other Waikato lakes have been reported by Lowe et al. (1981), Lowe (1986a, b), and Hogg et al. (1987).

The primary aim of this paper is to document the field properties, stratigraphy, chronology, and composition of the late Quaternary tephras contained in sediments in cores from the lakes in the central Waikato region. The lacustrine tephras described and analysed range in age from c. 1800 to 17 000 years B.P., and were erupted from six volcanic centres of both rhyolitic and andesitic composition (Fig. 1). The tephras are identified and correlated with named eruptive units elsewhere by using their stratigraphic relationships and radiometric ages in combination with mineralogical and chemical criteria. New isopach maps are presented, and the pattern of distribution of the tephras and their emplacement mechanisms are also considered.

The use of such lake sediments or peats to erect a comprehensive tephrostratigraphy is unusual, and the Waikato lakes have provided the longest and most complete sequence of tephras yet investigated in New Zealand lakes or bogs (cf. Topping & Kohn 1973; Howorth et al. 1980; McGlone 1983; Lowe & Hogg 1986). Apart from Iceland (e.g., Thorarinsson 1981), studies specifically on tephras in bogs and lakes elsewhere have also been relatively sparse, particularly from sites containing more than just a few tephras, but they are becoming increasingly important (e.g., Borchardt et al. 1973; Westgate 1977; Davis 1985; Riehle 1985).

WAIKATO LAKES AND BOGS

Most of the small, typically peaty lakes in the central Waikato region originated c. 15 000–17 000 years ago, during the final stages of alluvial aggradation of the Hinuera Formation by the ancestral Waikato

River (McCraw 1967; Green & Lowe 1985; Lowe & Green 1987). The lakes were formed when antecedent valleys draining low Pleistocene hills were blocked by the volcaniclastic Hinuera deposits, which dammed the valley mouths. The lakes are shallow (<c. 8 m) and usually contain c. 3–4 m (occasionally 5–6 m) of soft, brownish-black (peaty) to olive-grey lacustrine muds or clays (known as dy or gyttja) containing the remains of small lake-dwelling plants and animals (Green 1979; Boubée 1983). They have low sedimentation rates (c. 0.1–0.2 mm/year) (Green & Lowe 1985). Occasionally vivianite is found in the sediments.

The subsequent development of many of these lakes was affected by the massive growth of large, c. 10–12 m deep ombrogenous peat bogs on the surface of the Hinuera sediments (Fig. 1; Davoren 1978). These bogs probably formed first in patches in swampy hollows and around the margins of shallow lakes (such as Lake Maratoto) on the Hinuera surface (McCraw 1967). They rapidly expanded and deepened after c. 10 000–12 000 years ago, probably in response to a net increase in rainfall and hence a rise in regional water tables (Green & Lowe 1985).

The record of tephra fallout provided by the Waikato lakes is more comprehensive than that of the adjacent peat bogs. Usually only about six disseminated tephras, chiefly from substantial rhyolitic eruptions, are detectable in the peat cores*. For tephrostratigraphic purposes, the lakes are advantageous in that:

(1) they are older and contain a longer record;

(2) they have soft, fine sediment and (in the deeper basins) a relatively undisturbed environment that has allowed the preservation, as separate units, of deposits only a few millimetres in thickness; and

(3) the continuous lake cores provide unequivocal stratigraphic control.

Nevertheless, the tephrostratigraphy of the peat bogs is useful where lakes are lacking, especially in

mapping and dating tephras not otherwise identifiable in subaerial environments (e.g., Hogg & McCraw 1983). The results of the peat coring are excluded from this paper, but some preliminary findings are given in Green & Lowe (1985) and Hogg et al. (1987).

CORING SITES AND METHOD

Locations of the lakes cored in this study are shown in Fig. 1. Around 80 cores, usually c. 2–4 m in length, were obtained from the lakes with a hand-operated, modified Livingstone piston sampler (after Rowley & Dahl 1956). The coring tubes comprised lengths of PVC pipe of 50 mm internal diameter that were previously sawn in half longitudinally and held together with waterproof plastic tape. After the coring operation, the cores were split longitudinally using fine wire. Normally, several cores were taken from each lake, usually from the deepest areas, but occasionally from sites in shallower water or at the shoreline.

STRATIGRAPHY AND FIELD PROPERTIES OF THE TEPHRAS

The stratigraphy and main field properties of the tephras in the lake cores are summarised in Table 1 and Fig. 2. The stratigraphic sequence, thickness, lithology, and bedding characteristics of the tephra layers are practically identical in all of the lakes examined, hence they are regarded as representing primary airfall tephras. Further support for an airfall origin is given by Lowe (1985) in that the tephras in Lake Maratoto, although uneven in thickness, are

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*These include Taupo, Mamaku, Rotoma, Waiohau, and Rotorua tephras in the Hamilton Basin and, additionally, Kaharoa and Whakatane tephras in the Matamata Basin (Lowe 1987).

(*Notes to Table 1*)

*References for definitions of Taupo, Okataina, and Maroa derived correlative tephras are: Healy (1964); Vucetich & Pullar (1964, 1969, 1973); Lloyd (1972); Froggatt (1981c, d).

†Group–Subgroup designations: 1 = Lake Taupo Group, Taupo Subgroup; 2 = Okataina Group, Rotorua Subgroup (Howorth et al. 1981); 3 = no formal group status. Tuhua Tephra Formation was defined by Hogg & McCraw (1983); it is probably equivalent to the Oira Pyroclastite Formation (Mayor Island Group) of Buck et al. (1981), which applies to deposits on Mayor Island only; 4 = Tongariro Subgroup (Topping 1973).

‡Some ages interpolated from sedimentation rates (see text and Fig. 6).

ªInformally named Egmont derived tephras.

ᵇDefinition of Froggatt (1981c) and Lowe (1986a).

ᶜPossibly Te Rato Lapilli member (symbol Tt) (Lowe et al. 1980).

ᵈMembers of Okupata Tephra Formation informally designated Oa–1 to Oa–8; last is tentatively correlated with the "basal lapilli" unit of Topping (1973) (see text).
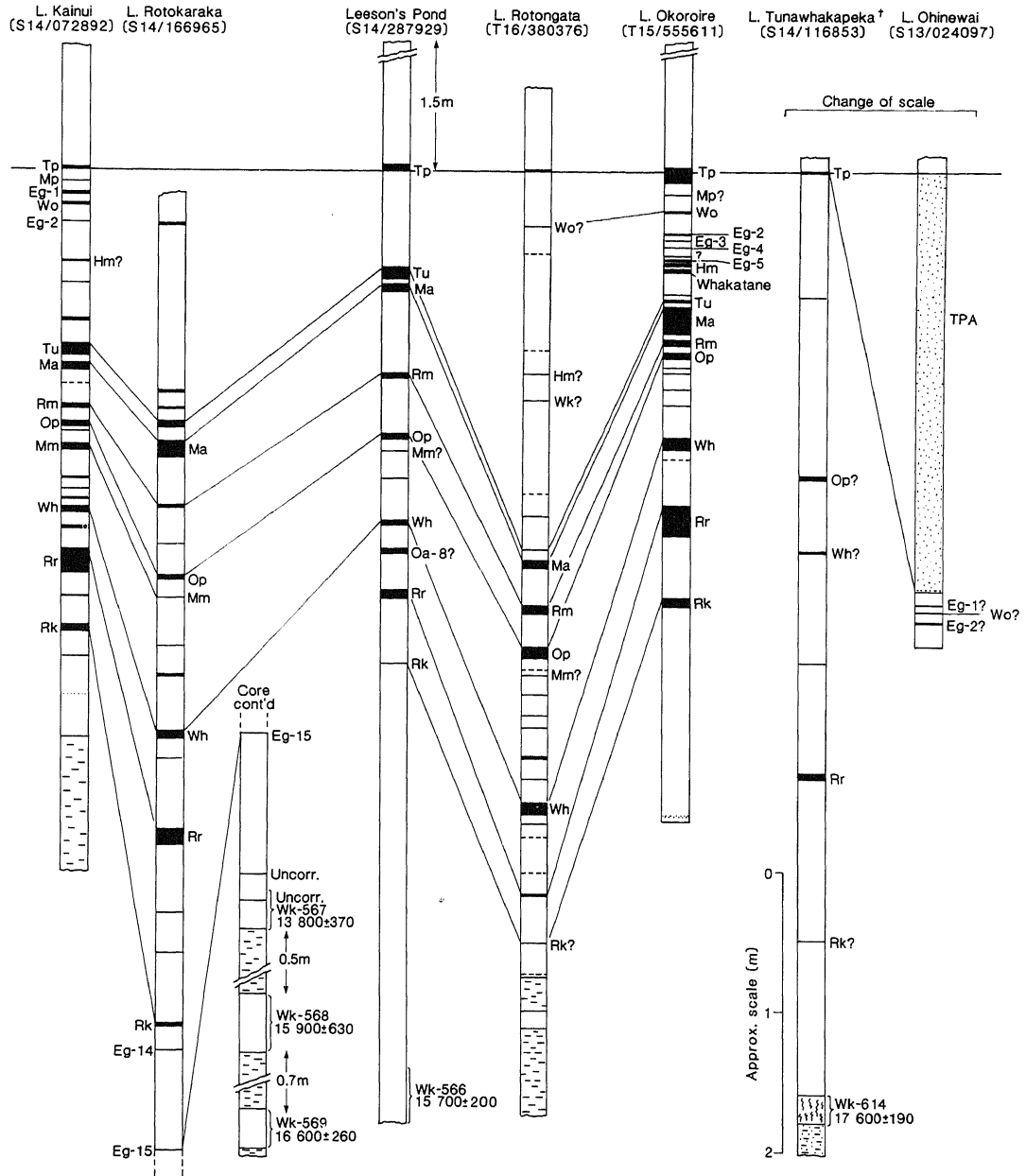
Table 1 Composite stratigraphic column of late Quaternary tephras identified in cores fromWaikato lakes. Some identifications are provisional.

Tephra and symbol (see Fig. 2)*	Source	Group–Subgroup†	Age (years B.P., old $T^1/_2$)‡	General description and approximate thickness range; comments
Taupo Pumice, Tp	Taupo	1	1800	Yellowish fine lapilli & coarse ash, 5–50 mm thick
Mapara Tephra, Mp	Taupo	1	2200	White fine ash, 2–3 mm
Egmont–1, Eg–1ᵃ	Egmont	–	2500	Grey fine–medium ash, 3–5 mm
Whakaipo Tephra, Wo	Taupo	1	2800	Greyish-white fine ash, 2–10 mm
Egmont–2, Eg–2	Egmont	–	3700	Brownish-grey, slightly speckled medium–coarse ash, 3–5 mm
Egmont–3, Eg–3	Egmont	–	3750	Indistinct fine ash, 1–2 mm (found only in L. Okoroire)
Egmont–4, Eg–4	Egmont	–	4100	Dark, medium–coarse ash, 1–3 mm; blotchy
Egmont–5, Eg–5	Egmont	–	4400	Pale yellowish-white, brownish-speckled, fine–medium ash, 3–6 mm
Hinemaiaia Tephraᵇ, Hm	Taupo	1	4500	White fine ash, 1–8 mm
Whakatane Ash, Wk	Okataina	2	4800	White fine–medium ash, 10–12 mm in L. Okoroire; possibly microscopic in other lakes
Egmont–6, Eg–6	Egmont	–	5250	Yellow fine ash, 2–3 mm
Egmont–7, Eg–7	Egmont	–	5850	Greyish–brown fine–medium ash, 1–2 mm
Egmont–8, Eg–8	Egmont	–	5900	Indistinct pale yellow fine ash, 1–2 mm
Tuhua Tephra, Tu	Mayor Is.	3	6200	Olive, greenish-grey fine–coarse ash, 5–45 mm
Mamaku Ash, Ma	Okataina	2	7000	Pale yellowish-brown to orange, fine–coarse ash, 20–80 mm; usually bedded
Rotoma Ash, Rm	Okataina	2	8500	Pale yellowish-white fine ash, 3–30 mm
Opepe Tephra, Op	Taupo	1	8900	Greyish fine ash, 10–20 mm (medium–coarse ash in L. Okoroire)
Egmont–9, Eg–9	Egmont	–	9300	Yellowish–white, speckled medium ash, 1–3 mm; may be disseminated (c. 10 mm); age approx.
Egmont–10, Eg–10	Egmont	–	9600	Yellowish medium ash, 1–2 mm; age approx.
Mangamate Tephra, Mmᶜ	Tongariro	4	9950	Mainly greyish-black, white speckled base, coarse ash, 5–20 mm; scoriaceous
Okupata Tephra, Oa–1ᵈ	Tongariro	4	10 100	Pale grey fine ash, 2–3 mm
Egmont–11, Eg–11	Egmont	–	10 100	Pale grey fine ash, 2–3 mm
Okupata Tephra, Oa–2	Tongariro	4	10 500	Indistinct brownish fine–medium ash, 1–2 mm; age approx.
Okupata Tephra, Oa–3	Tongariro	4	10 800	Indistinct brownish fine–medium ash, 1–2 mm; age approx.
Okupata Tephra, Oa–4	Tongariro	4	11 050)	Greyish-white, speckled, mainly medium–coarse ash but
Egmont–12, Eg–12	Egmont	–	11 050)	some fine ash 4–5 mm
Okupata Tephra, Oa–5	Tongariro	4	11 200	Pale greyish–white fine ash, 2–3 mm; age approx.; contains traces of Eg–tephra(?)
Okupata Tephra, Oa–6	Tongariro	4	11 700	Yellowish fine ash, 2–3 mm; may be blotchy or disseminated (c. 5–10 mm)
Okupata Tephra, Oa–7	Tongariro	–	12 100	Indistinct brownish fine ash, 1 mm; age approx.
Waiohau Ash, Wh	Okataina	2	12 200	White with cream top, fine–medium ash, 10–45 mm; commonly bedded
Okupata Tephra, Oa–8ᵈ	Tongariro	4	12 700	Greyish–brown to brown fine ash, 5–20 mm; occasionally disseminated (c. 50 mm)
uncorrelated, un	Tongariro	4	13 100	Brownish-grey fine–coarse ash, 3–5 mm; occ. bedded; age approx.
Rotorua Ash, Rr	Okataina	2	13 300	White mainly coarse ash, 15–110 mm; distinctly bedded (see Fig. 4)
Rotoaira Lapilli, Rt	Tongariro	4	13 700	Greyish fine–medium ash, 2 mm; usually disseminated (c. 30 mm); age approx.
Puketarata Ash, Pk	Maroa	–	14 000	Indistinct disseminated fine ash; contains traces of Eg–tephra(?); age approx.
Egmont–13, Eg–13	Egmont	–	14 500)	Indistinct pale yellowish-brown fine to v. fine ash;
uncorrelated, un	Mayor Is.	3	14 500))	Mayor Is. tephra occurs as glass only (micro-scopic); ages approx.
Rerewhakaaitu Ash, Rk	Okataina	2	14 700	White fine–coarse ash, wavy boundaries, 5–30 mm; some biotite flakes visible
Egmont–14, Eg–14	Egmont	–	15 000	Brownish, white-speckled coarse–medium ash, 1–2 mm
Egmont–15, Eg–15	Egmont	–	15 500	Brown fine ash, 1 mm; age approx. (see Fig. 6)
Okareka Ash, Ok	Okataina	2	17 000	Yellowish-white fine ash over coarse ash, 50 mm; biotite flakes common; age approx.

⇐ Definitions on facing page
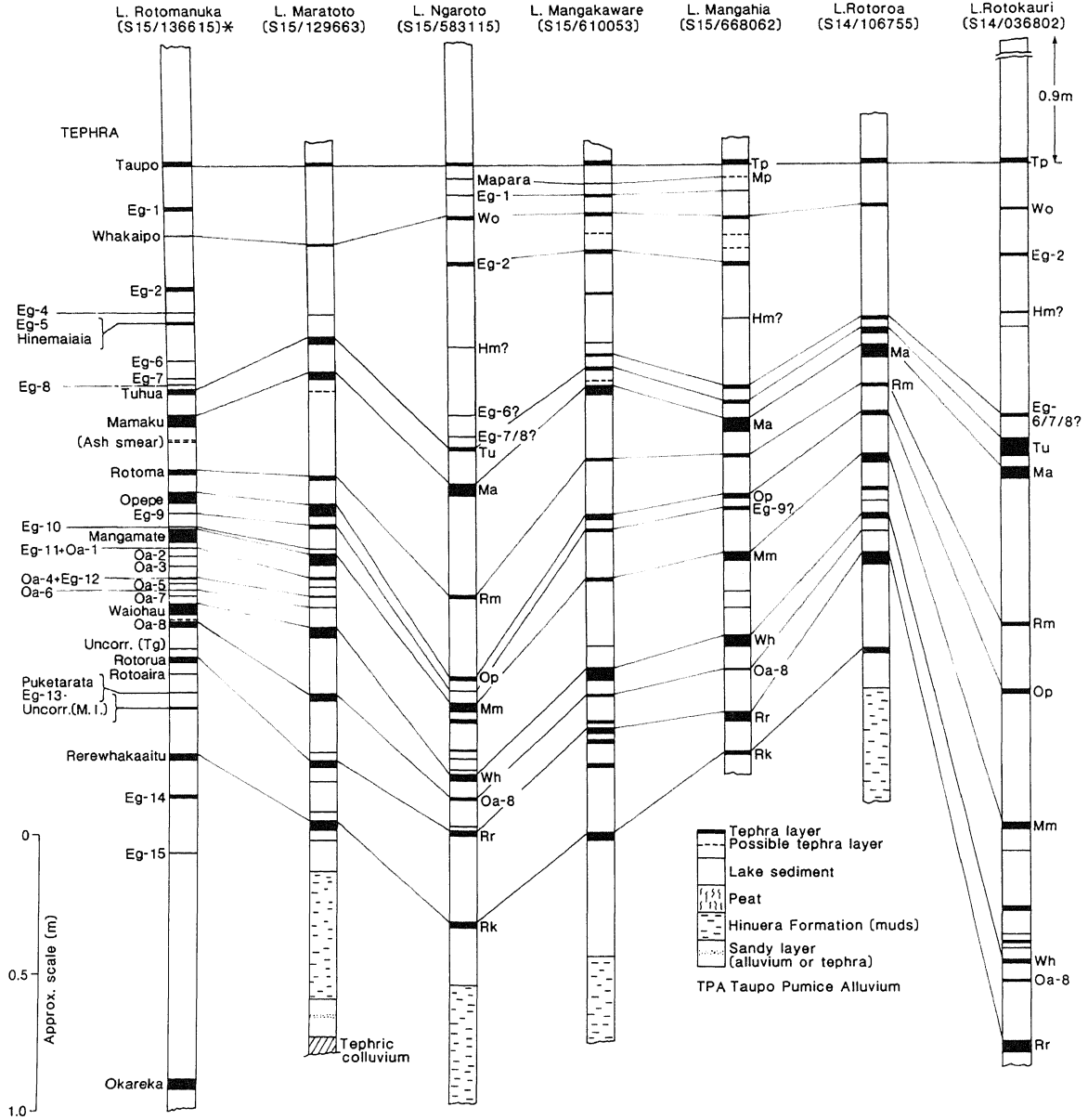
Fig. 2 Stratigraphy and correlation of late Quaternary tephras in cores from 14 Waikato lakes. Tephra names are explained in full in Table 1; Eg-1 to Eg-15 = Egmont derived tephras, informally numbered 1–15 with increasing age; Oa-1 to Oa-8 = informal units, numbered 1–8, of Okupata Tephra Formation; uncorr. = uncorrelated tephra (Tg = Tongariro source; M.I. = Mayor Island source). The chronology of the tephras is given in Fig. 6; additional ^{14}C dates given here (Wk- numbers) are in years B.P. The columns depicted are composites of two or more cores from each lake (hence scale is approximate because of differences in sediment thicknesses from core to core), as follows:

L. Kainui L. Rotokaraka
(S14/072892) (S14/166965)

Leeson's Pond
(S14/287929)

L. Rotongata
(T16/380376)

L. Okoroire
(T15/555611)

L. Tunawhakapeka[†] L. Ohinewai
(S14/116853) (S13/024097)

Change of scale

1.5m

Tp
Mp
Eg-1
Wo
Eg-2

Hm?

Tu
Ma

Rm
Op
Mm

Wh

Rr

Rk

Wh

Rr

Rk
Eg-14

Eg-15

Ma

Op
Mm

Wh

Rr

Rk

Tp

Tu
Ma

Rm

Op
Mm?

Wh

Oa-8?

Rr

Rk

Core
cont'd

Eg-15

Uncorr.
Uncorr.
Wk-567
13 800±370

0.5m

Wk-568
15 900±630

0.7m

Wk-569
16 600±260

Wk-566
15 700±200

Wo?

Hm?

Wk?

Ma

Rm

Op
Mm?

Wh

Rk?

Tp
Mp?
Wo
Eg-3 Eg-2
? Eg-4
Hm Eg-5
Whakatane
Tu
Ma
Rm
Op

Wh

Rr

Rk

Tp

Op?

Wh?

Eg-1? Wo?
Eg-2?

TPA

Rr

Rk?

Approx. scale (m)

0

1

2

Wk-614
17 600±190

L. Rotomanuka, 14 cores; L. Maratoto, 33 (see Green & Lowe 1985); L. Ngaroto, 2; L. Mangakaware, 3; L. Mangahia, 3; L. Rotoroa (= Hamilton Lake), 2; L. Rotokauri, 2; L. Kainui (= Lake D), 2; L. Rotokaraka, 4; Leeson's Pond, 3; L. Rotongata, 4; L. Okoroire, 3 (see Lowe 1986a); L. Tunawhakapeka† (drained "Rototuna Lake"), 1; L. Ohinewai, 2. *Approximate grid reference of coring site based on the national 1000 m grid of the 1:50 000 topographical map series (NZMS 260). †This lake was cored using a motorised Gidding's auger.

laterally continuous and generally follow the lake basin topography. It is possible that some of the tephric material derives from co-ignimbrite ashfall (see section on tephra distribution and implications below).

Most of the tephra layers can be readily correlated from core to core and from lake to lake using their field properties and stratigraphy (e.g., Fig. 3). The sources and identifications of the tephras given in Fig. 2 and Table 1 are based on their mineralogical and chemical composition and their age, as described in later sections, together with their stratigraphic relationships.

Tephra properties

Generally, most of the tephras occurring within the lake sediment are compact, macroscopic layers ranging in thickness from c. 2 mm to c. 110 mm. The layers are usually continuous (i.e., go right across the core), but occasionally they are partly dislocated or appear as ashy "pods" within the sediment. Upper contacts are commonly smooth in appearance but the overlying sediments usually contain indistinct ash grains disseminated over some millimetres; the lower contacts are often irregular and wavy but sharp (Fig. 3).

The thick tephras (i.e., > c. 5–10 mm) are typically pale coloured (white or grey, sometimes stained yellowish-orange) and stand out against the darker lake sediment (Fig. 3). They are usually glassy, pumiceous, and of rhyolitic origin. (An exception is the Mangamate Tephra which is greyish-black and andesitic.) Texturally, they range from fine ash (<c. $1/16$ mm) to fine lapilli (c. 2–4 mm), but commonly comprise medium (c. $1/16$–$1/2$ mm) or coarse (c. $1/2$–2 mm) ash. Normal or multiple graded bedding occurs frequently (e.g., Fig. 4A, B), especially in beds ≥c. 15 mm thick. Reverse grading is rare, however. Generally, these thicker tephras are the most distinctive and thus the most useful sediment markers in the cores. They include Taupo, Tuhua, Mamaku, Opepe, Mangamate, Waiohau, Rotorua, Rerewhakaaitu, and Okareka tephras (Fig. 2; Green & Lowe 1985).

The thin tephra beds (i.e., <c. 5 mm) are commonly darker coloured (dark grey, brown), often speckled and more crystal rich, rather indistinct, and of andesitic origin. The dark colour in some is due to staining by lake sediment. Some beds are greyish-white and yellowish-brown and can be either andesitic or rhyolitic in composition. Generally, these thinner beds consist of fine or medium–coarse ash and usually show little or no graded bedding, being well sorted.

Other tephras occur as diffuse, gritty zones in the lake sediments that may span up to c. 100 mm, or as very thin (<c. 1–2 mm), virtually microscopic layers best seen by X-radiography (Fig. 5; Lowe et al. 1981).

Bioturbation and stratigraphic reliability

Many of the tephras have irregular or diffuse contacts, or are manifest as relatively thin, indistinct zones within the sediments. Ash-filled burrow (?) channels may extend well below the base of some; gas-pocket holes may also occur (Fig. 4B). Most of this dissemination and disruption is short range and is probably attributable to bioturbation. (Other processes such as wave action, particularly near the lake margins, may also be important, e.g., Green & Lowe 1985.) The chief biological mixing agents are probably chironomids (tube formers) and other insect larvae, oligochaete worms, and crustacea (e.g., cladocerans such as chidorids), which tend to predominate in the sediments in shallow water near lake shores (Boubée 1983; J. D. Green pers. comm. 1987). Chironomid larvae can burrow up through ash layers at least 6 mm thick (Edmondson 1984).
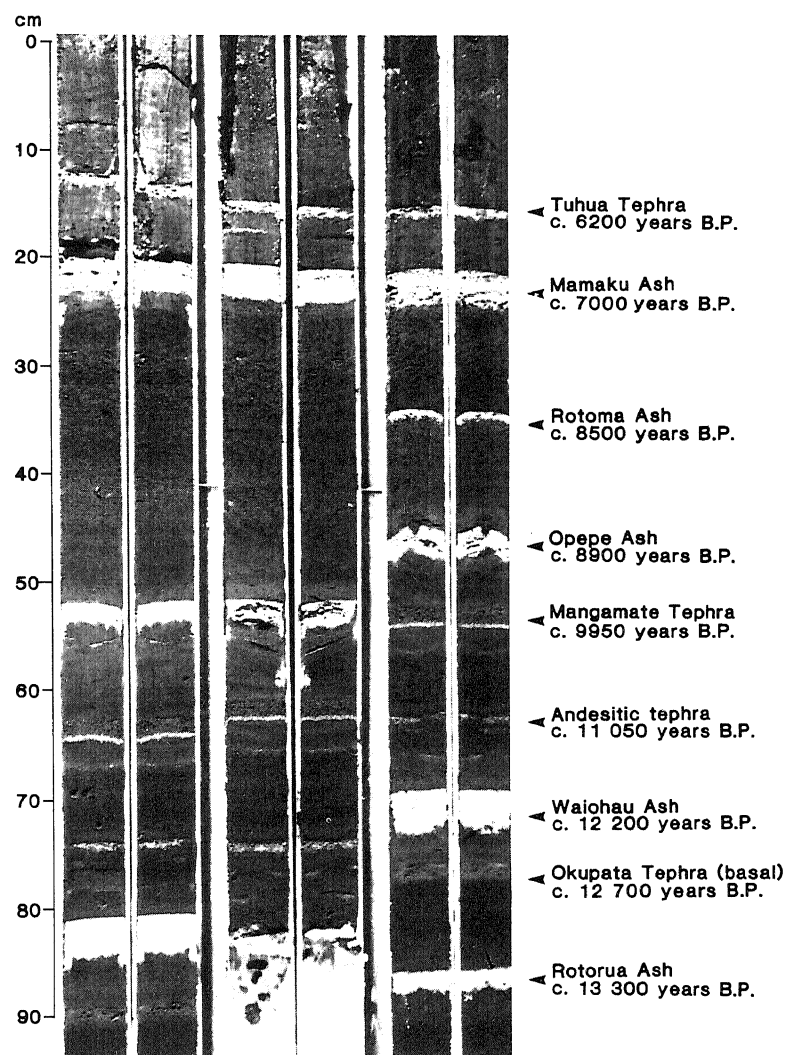
The effect of this bioturbation on the stratigraphic relationships of the tephras has, in general, been minor, and is usually visible and hence avoidable in sampling. The rates of sediment deposition, although relatively slow, have generally been sufficient to separate each successive tephra deposit with an intervening layer of sediment. Where tephras occur very closely together in the cores (i.e., within a few millimetres of one another) they may show some intermixing (detected by mineralogical or electron microprobe analysis described below).

Most tephras in the cores occur as essentially unmixed and discrete units which systematically increase in age with increasing depth (see chronology section), and clearly represent, to a large degree, a faithful stratigraphic record of tephra deposition (cf. Sarna-Wojcicki et al. 1981; Anderson et al. 1984). It is possible that some of the tephric material in the lakes was washed or blown in from the catchment (e.g., see Thompson et al. 1986), or reworked by wave action or currents soon after the main fall event, but any material so reworked effectively has the same age as the original fallout tephra (Fisher & Schmincke 1984).

Tephra duplication in the cores (e.g., Anderson et al. 1984) does not seem to have occurred—all but one of the tephra layers identified could be matched with known eruptions (or with known periods of

Fig. 3 Three longitudinally sliced cores from Lake Rotomanuka showing prominent, compact, ash-grade tephra layers preserved within dark, fine-grained organic lake sediment. The slight upward curvature of some of the beds is a function of the piston-coring technique. The "Andesitic tephra" in these cores may comprise two units, from Tongariro (Oa-4) (predominant) and Egmont (Eg-12), which have the same ^{14}C age (see text).

(*Photo: R. R. Julian*)

Tuhua Tephra
c. 6200 years B.P.

Mamaku Ash
c. 7000 years B.P.

Rotoma Ash
c. 8500 years B.P.

Opepe Ash
c. 8900 years B.P.

Mangamate Tephra
c. 9950 years B.P.

Andesitic tephra
c. 11 050 years B.P.

Waiohau Ash
c. 12 200 years B.P.

Okupata Tephra (basal)
c. 12 700 years B.P.

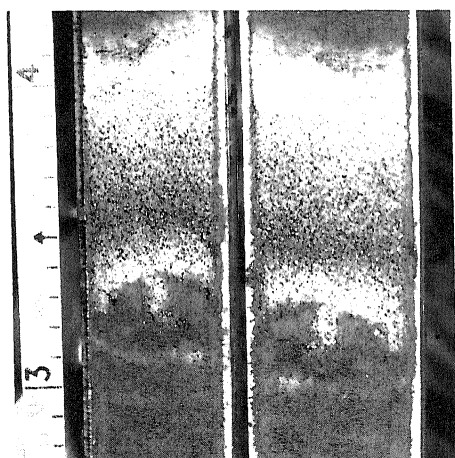Rotorua Ash
c. 13 300 years B.P.

activity) from the North Island volcanoes. The "unknown" (rhyolitic) layer, found intermittently between Mamaku Ash and Rotoma Ash in a few cores (Fig. 2), probably resulted from reworking of one or both of these tephras, either naturally or by a smearing action brought about by the coring method in its initial period of use (Lowe 1987).

## Number of eruptives and total thickness of deposits

Forty one tephras have so far been identified in the lakes. A few of the tephras are microscopic units and were detected by electron microprobe analysis of sparse glass shards or titanomagnetite grains. Not all of the tephras occur in any one core, nor in one single

lake. The longest and most detailed record of all the lakes cored is found in Lake Rotomanuka (Fig. 2), which, together with the centrally located Lake Maratoto, has been the focus of most laboratory analysis.

The total thickness of the visible lacustrine tephras in the Ohaupo–Hamilton area is, on average, c. 25 cm (Table 2). In the northern Waikato (e.g., Lakes Rotokaraka, Leeson's Pond) the average thickness is estimated at c. 15–20 cm, and in the east (e.g., Lake Okoroire), c. 40–45 cm. These thicknesses are approximate because the irregular boundaries and diffuse nature of some of the tephras can make measurements imprecise. Also, the thickness of individual tephras may differ in cores from the same lake.

Fig. 4A   Normally graded Rotorua Ash Formation, Lake Okoroire, comprising mainly pumiceous coarse ash overlain by fine ash (latter contains very sparse fine lapilli). Scale marks are 1 cm apart.
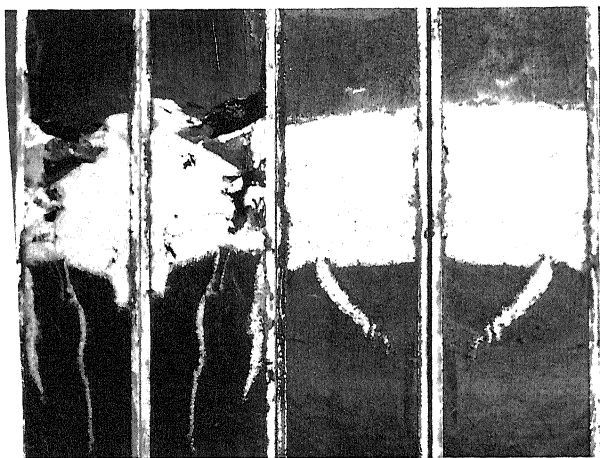
Fig. 4B   Rotorua Ash Formation in two cores from Lake Kainui, showing multiple bedding (from base up have medium ash, fine ash, pumiceous coarse ash, medium ash, fine ash), gas-pocket holes (core on left), and coarse ash-filled burrow(?) channels underneath the tephra. Scale marks are 1 cm apart.

Relationship to thickness of subaerial deposits

The very firm, compact nature of most of the thicker lacustrine tephras contrasts with the friability and low bulk densities (c. 0.7–0.9 g/cm^3) commonly associated with their subaerial equivalents (e.g., Gradwell 1982). The lacustrine tephras are coherent and probably have bulk densities of c. 1.5 g/cm^3, based on their field properties and measurements made on tephras in similar settings by Borchardt et al. (1973) and Anderson et al. (1984). Rai (in Borchardt et al. 1973) estimated from bulk density comparisons that onland tephras are about 1.75 times as thick as equivalent bog or lacustrine tephras. Similarly, Watkins et al. (1978) and Sparks et al. (1983) converted submarine tephra thicknesses to equivalent dry-land (original) thicknesses by correcting for the effects of compaction and bioturbation. Thus, the expected equivalent dry-land tephra thicknesses in the Waikato area may be roughly estimated, in part, by using a compaction correction factor of 1.75 (Table 2). An additional correction for dissemination can be made using the results of X-radiography. In a short core from Lake Mangakaware, the total thickness of visible tephras is 43 mm; the X-radiograph or "true" thickness is 53 mm (see Lowe et al. 1981). Thus, visual measurements of tephra thickness may underestimate the true thickness by c. 20%. Because only a few cores were X-rayed, it is not known if this value applies generally, but it seems reasonable to conservatively adopt 10% as a correction for dissemination. Therefore 10% of the original visible thickness measurements may be added to the compaction-corrected thickness to obtain a total equivalent dry-land thickness (Table 2). These recalculated figures are generally consistent with thickness measurements of subaerial tephra profiles at various sites in the Waikato region (e.g., Pullar 1967; Pullar & Birrell 1973b; Lowe 1986b).

CHRONOLOGY OF THE TEPHRAS

Sampling

Lake sediment enclosing the tephras was sampled for radiocarbon dating to determine the tephras' age of deposition and thus time of eruption. Stratigraphic columns showing the sampling positions with respect to the tephras identified are given in Fig. 6.

The slices of sediment, generally 1–2 cm thick, were extracted from above and below the tephra layers using stainless steel cutters. Although the slices were deliberately kept as thin as possible, they nevertheless represent an accumulation time of perhaps c. 100–200 years because of the slow rates of sedimentation in the Waikato lakes. Consequently, the dates obtained may be limited in their accuracy, with respect to the age of deposition of the tephras, by up to several hundred years. However, this potential reduction in accuracy is
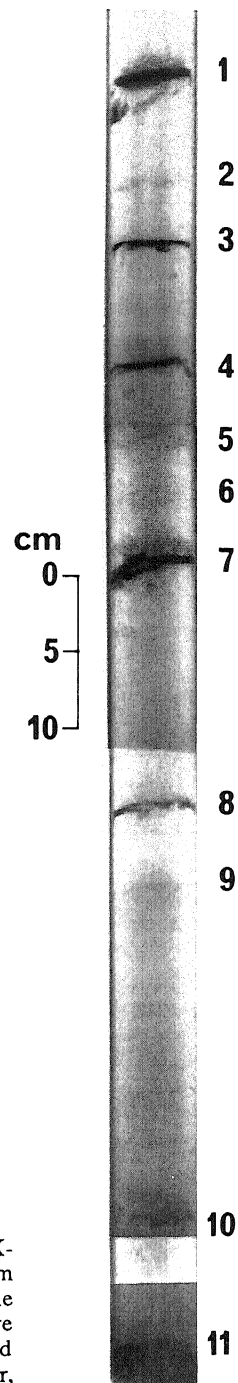
Fig. 5 Composite X-radiograph of a core from Lake Mangahia. The numbered tephras are provisionally identified from their field character, stratigraphic position, and age (based on estimated sedimentation rates) as follows: 1, Taupo Pumice; 2, Mapara Tephra; 3, Eg-1; 4, Whakaipo Tephra; 5,6, uncorrelated; 7, Eg-2; 8, Eg-5 or Hinemaiaia Tephra; 9, Eg-6(?); 10, Tuhua Tephra; 11, Mamaku Ash.   (*Photo: A. O. Vallinga*)

partly offset by the obtaining of a stratigraphic succession of dates in the cores from several sites, and by the availability of dates on many of the tephras in other environments (e.g., Pullar et al. 1973), which thus act as independent monitors of error (cf. Mathewes & Westgate 1980; Green & Lowe 1985).

To provide sufficient material for dating, slices of sediment from two or more suitable cores (taken in the same lake) commonly were combined into composite samples (organic contents generally decrease with increasing depth in the cores, with usually only c. 10% or less organic matter in the basal lake sediments; Green & Lowe 1985). The distinctive nature of most of the tephras ensured that this procedure could be carried out confidently because the same stratigraphical event in each core could be positively identified. Conversely, some indistinct tephras were accordingly not sampled for dating.
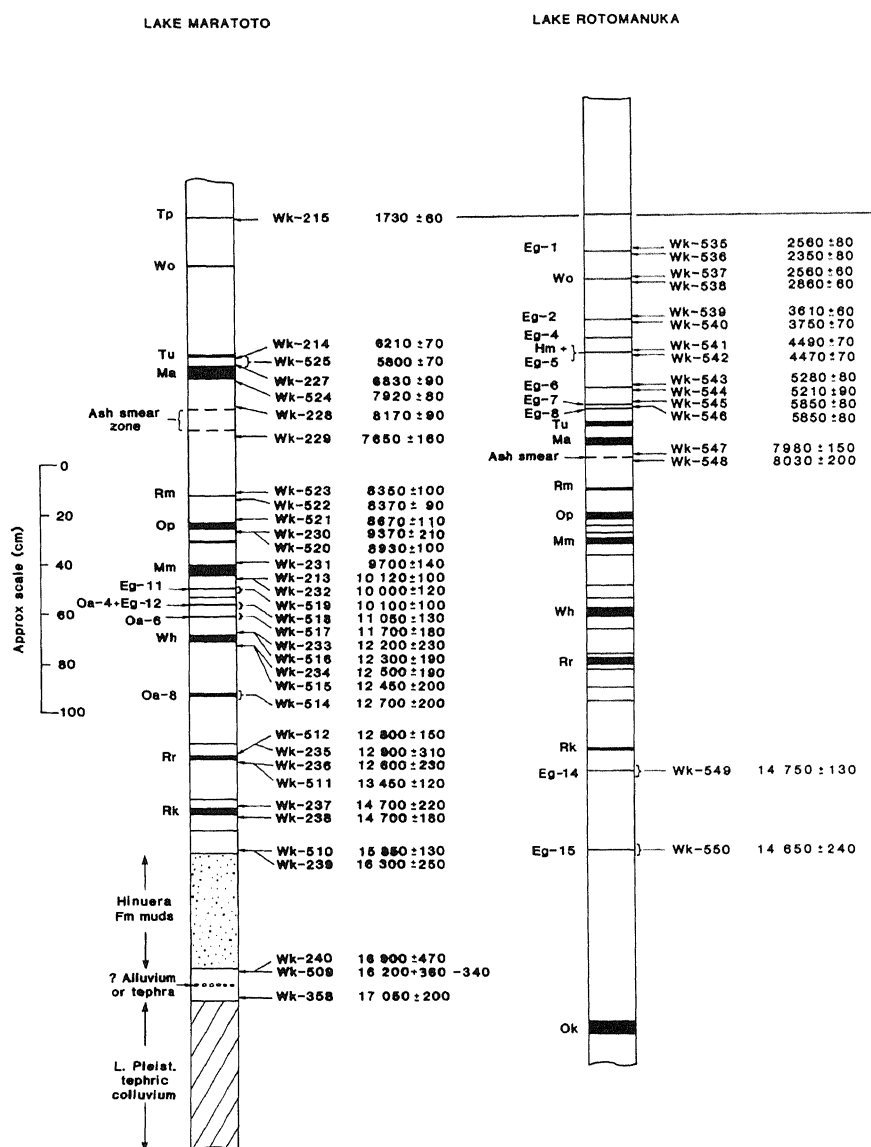
In samples with very low carbon contents, the slices from above and below the tephra were combined into a "straddle" sample, providing an average age for the tephra. Where tephras were closely spaced in the cores, the entire layer of sediment between two adjacent tephras (i.e., "bridging" them) was sampled. The date thus obtained applies equally to both tephras, giving a maximum age for one and a minimum age for the other (Hogg et al. 1987).

The samples were oven dried, lightly crushed, and submitted to the University of Waikato Radiocarbon Dating Laboratory (symbol Wk-) for ^{14}C assay. About 70 samples applying to tephras were dated.

Results and interpretation

The dates and associated error terms (one standard deviation) obtained from cores from five lakes are given in Fig. 6. Ages adopted in this study for the tephras are summarised in Table 1. Where a few specific tephra layers were not dated, their ages of deposition were interpolated using sedimentation rates. Ages so obtained are reasonably reliable because they are well constrained by the dates on material in adjacent parts of the core.

The ages accord with the stratigraphy (increase down the cores) with few age inversions from tephra to tephra. Commonly, the dates above and below a tephra are statistically indistinguishable (using the method of Currie 1981). Some of the dates on the mainly inorganic basal lake sediments (e.g., Wk-240, -504) have large errors that reflect heavy dilution in the dating procedure because of a low

LAKE MARATOTO   LAKE ROTOMANUKA

Tp   Wk-215   1730 ± 60
Wo
                                              Eg-1   Wk-535   2560 ± 80
                                                        Wk-536   2350 ± 80
                                              Wo   Wk-537   2560 ± 60
                                                        Wk-538   2860 ± 60

                                              Eg-2   Wk-539   3610 ± 60
                                                        Wk-540   3750 ± 70
Tu   Wk-214   6210 ± 70   Eg-4
Ma   Wk-525   5800 ± 70   Hm +   Wk-541   4490 ± 70
            Wk-227   6830 ± 90   Eg-5   Wk-542   4470 ± 70
            Wk-524   7920 ± 80   Eg-6   Wk-543   5280 ± 80
Ash smear   Wk-228   8170 ± 90   Eg-7   Wk-544   5210 ± 90
zone   Eg-8   Wk-545   5850 ± 80
            Wk-229   7650 ± 160   Tu   Wk-546   5850 ± 80
                                              Ma
                                              Ash smear Wk-547   7980 ± 150
0   Wk-548   8030 ± 200
Rm   Wk-523   8350 ± 100   Rm
20   Wk-522   8370 ± 90
Op   Wk-521   8670 ± 110   Op
            Wk-230   9370 ± 210
            Wk-520   8930 ± 100   Mm
40
Mm   Wk-231   9700 ± 140
Eg-11   Wk-213   10 120 ± 100
Oa-4+Eg-12 Wk-232   10 000 ± 120
60   Wk-519   10 100 ± 100   Wh
Oa-6   Wk-518   11 050 ± 130
Wh   Wk-517   11 700 ± 180
            Wk-233   12 200 ± 230
            Wk-516   12 300 ± 190   Rr
80   Wk-234   12 500 ± 190
            Wk-515   12 450 ± 200
Oa-8   Wk-514   12 700 ± 200
100
            Wk-512   12 800 ± 150
Rr   Wk-235   12 900 ± 310   Rk
            Wk-236   12 600 ± 230
            Wk-511   13 450 ± 120   Eg-14   Wk-549   14 750 ± 130

Rk   Wk-237   14 700 ± 220
            Wk-238   14 700 ± 180

            Wk-510   15 850 ± 130   Eg-15   Wk-550   14 650 ± 240
            Wk-239   16 300 ± 250

Hinuera
Fm muds
            Wk-240   16 900 ± 470
? Alluvium Wk-509   16 200 +360 -340
or tephra
            Wk-358   17 050 ± 200

                                              Ok
L. Pleist.
tephric
colluvium

Table 2 Total thickness of tephras* younger than and including Rerewhakaaitu Ash in the Waikato area based on lake core measurements, and estimated equivalent dry-land thicknesses. Values in millimetres.

Area	Total visible thickness in cores (average)	Compaction - corrected thickness (visible x1.75)	Estimated dissemination thickness (visible x0.1)	Total equivalent dry-land thickness (approx.)
Hamilton–Ohaupo	25	44	2.5	47
Whitikahu–Morrinsville	20	35	2.0	37
Okoroire–Tirau	42	74	4.2	78

*Assumed to represent airfall material only, with no modification to thickness by postdepositional reworking or catchment erosion.
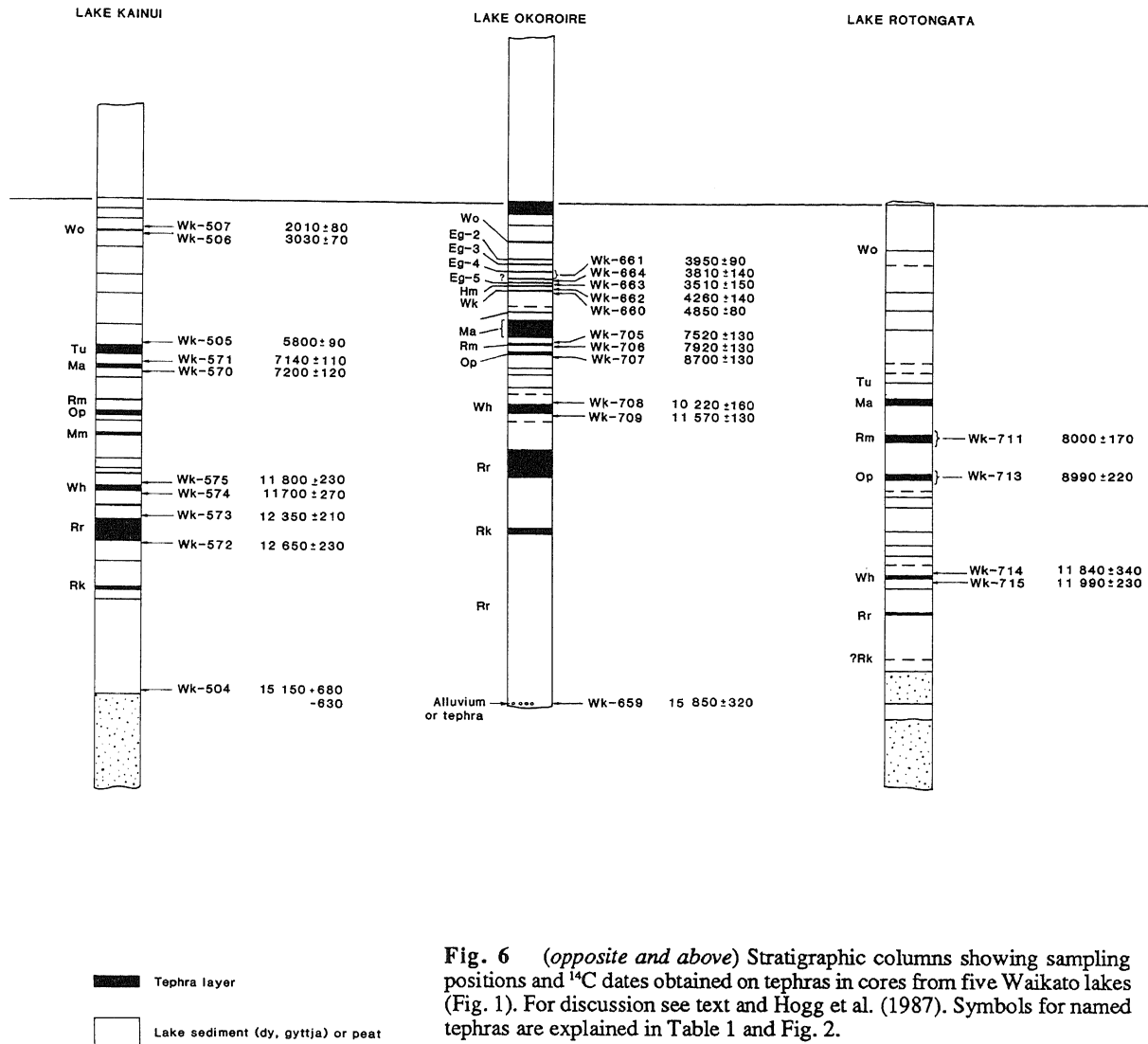
LAKE KAINUI

LAKE OKOROIRE

LAKE ROTONGATA

Wo ——— Wk-507   2010±80
          Wk-506   3030±70

Tu ——— Wk-505   5800±90
Ma ——— Wk-571   7140±110
          Wk-570   7200±120

Rm
Op
Mm

Wh ——— Wk-575   11 800±230
Wh ——— Wk-574   11700±270
          Wk-573   12 350±210
Rr
          Wk-572   12 650±230

Rk

          Wk-504   15 150+680
                          -630

Wo
Eg-2
Eg-3
Eg-4 ——— Wk-661   3950±90
Eg-5 ? ——— Wk-664   3810±140
Hm ——— Wk-663   3510±150
Wk ——— Wk-662   4260±140
          Wk-660   4850±80

Ma ——— Wk-705   7520±130
Rm ——— Wk-706   7920±130
Op ——— Wk-707   8700±130

Wh ——— Wk-708   10 220±160
          Wk-709   11 570±130

Rr

Rk

Rr

Alluvium ——— Wk-659   15 850±320
or tephra

Wo

Tu
Ma

Rm ——— Wk-711   8000±170

Op ——— Wk-713   8990±220

Wh ——— Wk-714   11 840±340
          Wk-715   11 990±230

Rr

?Rk

Tephra layer

Lake sediment (dy, gyttja) or peat

Fig. 6 (*opposite and above*) Stratigraphic columns showing sampling positions and ^{14}C dates obtained on tephras in cores from five Waikato lakes (Fig. 1). For discussion see text and Hogg et al. (1987). Symbols for named tephras are explained in Table 1 and Fig. 2.

carbon content and a small sample size (Hogg et al. 1987).

To a large extent the dates agree closely with those obtained for the same tephras elsewhere (e.g., Pullar & Heine 1971; Vucetich & Pullar 1973; Cole & Nairn 1975; Froggatt 1981a; Hogg & McCraw 1983), although relatively few dates are available for andesitic eruptives from Tongariro and Egmont (e.g., Topping 1973; Neall & Alloway 1986).

Anomalous ages are associated with the eruptions of the Okataina-derived Rotoma Ash (c. 8500 years B.P.?) and Waiohau Ash (c. 12 200 years B.P.?). Generally, the dates obtained on the lake

cores for Rotoma Ash are younger, and for Waiohau Ash, older, than those obtained at other sites (e.g., Pullar & Heine 1971; Nairn 1981); the differences in age amount to c. 500–1000 years or so. This discrepancy is discussed more fully in Green & Lowe (1985), Lowe & Hogg (1986), and Hogg et al. (1987). Some of the dates on Rotorua Ash are significantly younger than the normally accepted age of c. 13 450 years (Nairn 1980), although errors are quite large.

Okareka Ash, positively identified only in cores from Lake Rotomanuka (Fig. 2), was not dated directly in this study because enclosing sediment

contained insufficient carbon for normal ^{14}C laboratory requirements. An age of c. 17 000–18 000 years is suggested from approximate sedimentation rates. This age range is supported by consideration of the dates obtained for Lake Maratoto sediments, the oldest of which are 17 050 ± 200 years B.P. (Wk-358; Green & Lowe 1985). Because Okareka Ash is apparently absent from the Lake Maratoto sediments, then it is likely to be older than c. 17 000 years.

Elsewhere, Okareka Ash has not been dated, but Nairn (1981) estimated its age as c. 17 000 years based on its stratigraphic relationship to dated overlying (Rerewhakaaitu) and underlying (Te Rere, Kawakawa) tephras (Vucetich & Pullar 1969). An arbitrary age of c. 17 000 years is therefore adopted here (Table 1), but an older age may yet eventuate for this tephra.

TEPHRA COMPOSITION AND IDENTIFICATION

In hand specimen and under the binocular microscope the pale coloured rhyolitic tephras are predominantly vitric with both platy and sparsely porphyritic pumiceous shards. They also contain subordinate feldspar and mafic crystals or crystal fragments, commonly with glass selvedges. Lithic fragments are rare. The andesitic tephras, usually darker in colour, are composed mainly of feldspar and mafic crystals, often with narrow glassy selvedges, and of greyish, moderately vesicular, "andesitic scoria" comprising microlites or crystallites of feldspar and other constituents in a glassy matrix (see section on light minerals below). Glass shards are relatively uncommon and usually vesicular (e.g., see Kirkman & McHardy 1980), and may have a "dirty" appearance due to slight surficial weathering. Sparse lithics of varying composition may also occur.

Sampling and laboratory analysis

All the tephra layers in cores from Lakes Rotomanuka, Maratoto, and Kainui, and some of the tephras in Lakes Okoroire, Rotongata, and Mangahia, were sampled (a total of about 150 samples). The 63–250 μm (2–4 φ) size fractions of the samples of each of the tephras were split into heavy mineral (sp. gr. >2.9 g/cm^3) and light mineral (sp. gr. <2.9 g/cm^3) components using standard heavy liquid and Frantz electromagnetic methods (Lowe 1981a; Froggatt & Gosson 1982), and their

proportions were determined gravimetrically. These components were further separated and prepared as necessary for analysis by petrographical microscope (point count of detrital mounts), X-ray diffraction (XRD) (powder mounts), scanning electron microscope (SEM) (unpolished and polished mounts), and electron microprobe (EMP) (polished blocks of various constituents) (Lowe 1981a; Froggatt & Gosson 1982; Hume & Nelson 1982; Froggatt 1983).

Correlations with source volcanoes and named eruptives

The analytical results, when considered together and with reference to previous work, permit the correlation of each of the distal tephras to one of six volcanic centres (Fig. 1; Lowe in press). The main diagnostic criteria are summarised in Table 3. By taking into account the tephras' stratigraphic position and age, correlations with named proximal eruptives from each of these source volcanoes have been established (stratigraphic names are summarised in Table 1).

Several modifications to the provisional tephrostratigraphy recorded in Lowe et al. (1980) are made. "Waimihia Lapilli" is re-identified here as Whakaipo Tephra (see glass chemistry section below). "?Rotoma Ash" and "Unnamed ash" were re-identified as Mamaku Ash and Rotoma Ash, respectively, by Green & Lowe (1985). "?Okato Tephra" is re-identified here as the lowest unit of the Okupata Tephra Formation (Oa-8), taken to be equivalent to the "basal lapilli" bed described by Topping (1973). Dates on Okupata Tephra near source are (NZ1374) 9790 ± 160 years B.P. (min.) and (NZ1189) 12 450 ± 340 years B.P. (max.) (Topping 1973, p. 410). In addition, the formation is overlain by Karapiti Tephra and underlain by an unnamed andesitic tephra and Rotorua Ash (Topping & Kohn 1973; Froggatt & Solloway 1986), and hence its age is further constrained by the ages of these tephras. From these ages and the descriptions in Topping (1973) it appears that Okupata Tephra Formation is time transgressive, with units erupted at various intervals between c. 10 000 and c. 12 500–13 000 years ago. (A member of Okupata Tephra Formation is dated at c. 10 300 years B.P. in Lowe & Hogg 1986.) Consequently, andesitic tephras with Tongariro source characteristics that occur between Mangamate Tephra (?Te Rato Lapilli) and Rotorua Ash in the lake cores might best be considered as representatives of the Okupata Tephra Formation.

Table 3 Summary of mineralogical and compositional criteria characterising tephra sources (eruptions since c. 20 000 years ago).

Source volcano	Heavy minerals					Glass: feldspar ratio[c]	Light minerals		
	H.M. in 2–4φ (%)[a]	Opaques in H.M. (%)[a]	Dominant ferromagnesian minerals[b]	Clino-pyroxene composition	Fe-Ti oxide composition		Glass composition (mean%)[d]	Feldspar composition	P.I. (mean)[e]
Taupo	4±5	19±8	Hyp ± Aug	–	–	H	Rhyolitic: SiO_2 76.90±0.52 TiO_2 0.20±0.04 FeO 1.66±0.15 MgO 0.17±0.04 CaO 1.26±0.13	Sodic plagioclase (olig. – and.)	64.0
Okataina	2±2	26±9	Hbe + Hyp + Aug ± Cgt ± Bio	–	–	H	Rhyolitic: SiO_2 78.52±0.32 A. TiO_2 0.11±0.04 FeO 0.90±0.08 MgO 0.11±0.02 CaO 0.78±0.07 B. TiO_2 0.21±0.04 FeO 1.30±0.14 MgO 0.21±0.05 CaO 1.26±0.23	Sodic plagioclase (olig. – and.)	64.4
Maroa[f]	–	–	(Bio + Hbe ± Hyp)	–	–	(H)	Rhyolitic: SiO_2 78.46±0.49 TiO_2 0.07±0.03 FeO 0.87±0.18 MgO 0.07±0.02 CaO 0.68±0.09	–	67.2
Mayor I.	0.6±0.5	4±4	Aeg ± Aen ± Rie ± Olv	–	–	H	Rhyolitic: SiO_2 75.35±0.53 Peralkaline $[Na_2O+K_2O]/Al_2O_3 > 1$	Alkali (sanidine-anorth.)	81.4
Tongariro	15±5	9±6	Opx + Cpx ± Olv(fo) ±Hbe	wo$_{42±2}$	Cr_2O_3 0.2–0.3% MnO 0.3–0.5%	L	Andesitic: SiO_2 61.38±2.41 K_2O 1.82±0.43	Calcic plag. (labrad.-bytown.) mean an$_{61±8}$	71.8
Egmont	22±9	10±6	Cpx + Hbe ± Opx	wo$_{45±2}$	Cr_2O_3 <0.05% MnO 0.4–1.0%	L	Rhyo.-dacitic: SiO_2 70.46±2.19 K_2O 4.32±0.76	Calcic. plag. (labrad.-bytown.) mean an$_{57±9}$	81.7

[a]H.M. = heavy minerals (Table 4); proportions not likely to be entirely persistent because of eolian fractionation.
[b]Hyp = hypersthene; Aug = augite; Hbe = hornblende; Cgt = cummingtonite (dominant in Whakatane and Rotoma tephras; Table 5); Bio = biotite (dominant in Rerewhakaaitu and Okareka tephras; also important in Rotorua Ash; Table 5); Aeg = aegirine; Aen = aenigmatite; Rie = riebeckite; Olv = olivine; Cpx = clinopyroxene; Opx = orthopyroxene.
[c]H = high (glass ≥c. 80% of 2–4φ fraction); L = low (glass c. 15–45% of 2–4φ fraction).
[d]Anhydrous basis; A = Okataina tephras other than Rotorua Ash; B = Rotorua Ash; total Fe as FeO.
[e]Parker Index:

$$\left[\frac{(Na)_a}{(Na-O)_b} + \frac{(Mg)_a}{(Mg-O)_b} + \frac{(K)_a}{(K-O)_b} + \frac{(Ca)_a}{(Ca-O)_b} \right] \times 100$$

where $(X)_a$ = atomic proportion of element X, and $(X-O)_b$ = bond strength of element X with oxygen (Na-O = 0.35; Mg-O = 0.9; K-O = 0.25; Ca-O = 0.7) (Parker 1970).
[f]Puketarata Ash (identification tentative; see text); ferromagnesian assemblage based on Topping & Kohn (1973).
– indicates not measured or insufficient data.

Sig 2

Oa-8 is assumed to be a correlative of the basal lapilli unit of Topping (1973), and has a date of (Wk-514) 12 700 ± 200 years B.P. (Fig. 6). A thin andesitic tephra is found stratigraphically between this tephra (Oa-8) and the underlying Rotorua Ash (Rr) in some lake cores (Fig. 2) and, based on its proximity to the latter tephra, has an estimated age of c. 13 100 years. This tephra is regarded here as an "unnamed tephra" (cf. Topping 1973).

Informal designations are used where correlations are currently uncertain (e.g., for the Egmont eruptives, Eg-1 to Eg-15), and where no formal name has previously been defined (e.g., unnamed members of the Okupata Tephra Formation, Oa-1 to Oa-8). The analytical data from the heavy and light mineral fractions providing the basis for these correlations are presented and discussed below.

Heavy minerals

The 2–4 φ heavy mineral fractions consist chiefly of ferromagnesian silicates and ubiquitous Fe-Ti oxides (opaque minerals). Results from the gravimetric and modal analyses are summarised in Tables 4 and 5. Some samples contained insufficient heavy minerals for analysis.

Proportions of heavy and opaque minerals

Although the figures in Table 4 show considerable variation, some general trends are evident. The tephras from the rhyolitic Taupo and Okataina

Volcanic Centres are relatively low in heavy minerals (<5%) but high in Fe-Ti oxides (c. 20–30%), especially Okataina. The opposite applies to the andesitic Tongariro and Egmont derived tephras, which are high in heavy minerals (c. 15–25%) and relatively low in oxides (10%). Samples of the pantelleritic Mayor Island derived tephras are very low in both heavy minerals (1%) and oxides (5%). (The unnamed c. 14 500 year old Mayor Island tephra consists solely of glass, as does the Maroa derived Puketarata Ash.)

These trends in relative abundances are broadly similar to those of near-source eruptives, taking into consideration differences in methodology, size fractions examined, and type of sample: the andesitic tephras are relatively mafic rich and Fe-Ti oxide poor; the rhyolitic tephras are mafic poor but with variable, sometimes high, Fe-Ti oxide abundances (cf. Clark 1960; Ewart 1963; Gow 1968; Cole 1970, 1978; Kohn & Neall 1973; Buck et al. 1981; Neall et al. 1986). Some of the variations are likely to be due in part to the effects of eolian fractionation (e.g., see Fisher & Schmincke 1984; Juvigné & Porter 1985), as is evident particularly for the tephras consisting wholly of glass.

Ferromagnesian mineral assemblages

The ferromagnesian silicate minerals generally have properties similar to those described in Lowe (1981a). Most of the minerals are euhedral with glassy rims, and typically contain abundant inclusions such as apatite, glass, and opaque minerals.

The ferromagnesian assemblages (Table 5) can be classed into five main groups, each of which characterises one of the source volcanoes, as follows:

Group 1 (Taupo): Hypersthene ± augite. **Group 2 (Okataina):** Hornblende + hypersthene + augite ± cummingtonite ± biotite. **Group 3 (Tongariro):** Orthopyroxene + clinopyroxene ± olivine ± hornblende. **Group 4 (Egmont):** Clinopyroxene + hornblende ± orthopyroxene. **Group 5 (Mayor Island):** Aegirine ± aenigmatite ± riebeckite ± olivine ± ferro-hedenbergite ± tuhualite.

(The only recent eruptive from the Maroa Volcanic Centre, Puketarata Ash, contains mainly biotite and hornblende ± hypersthene near source; Topping & Kohn 1973.) Apatite and zircon may also occur in small amounts (<5%), with zircon being a noticeable constituent in the Okataina derived tephras in particular. The proportions of minerals within most groups may vary from sample to

Table 4   Abundances of heavy minerals and opaque minerals in 2-4φ fractions of tephras in Waikato lake cores. Values are mean ± 1 standard deviation; n = number of samples of tephras analysed for each volcanic centre.

Volcanic centre	Heavy minerals (wt.%)*	n	Opaque minerals (vol.%)†	n
Taupo	3.6 ± 4.6	10	18.9 ± 7.8	24
Okataina	1.7 ± 1.5	26	26.1 ± 9.4	38
Maroa	trace	1	0	1
Mayor Island	0.6 ± 0.5	4	4.3 ± 4.2	5
Tongariro	15.2 ± 5.4	15	9.1 ± 5.5	21
Egmont	22.1 ± 9.3	11	10.2 ± 6.1	25

*Proportion of heavy minerals in 2-4φ fractions. Values for samples containing sparse heavy minerals are liable to have low precision.
†Proportion, by point count, of opaque minerals in the 2-4φ heavy mineral fraction (see Table 5).
Samples from Lakes Rotomanuka, Maratoto, Kainui, and Okoroire.

Table 5 Dominant ferromagnesian minerals in tephras in cores from Waikato lakes and bogs.

	Taupo derived tephras					Okataina derived tephras						
	Tp	Mp	Wo	Hm	Op	Wk	Ma	Rm	Wh	Rr	Rk	Ok
Hyp	81–91	91	70–92	92	62–72	8–21	25–75	4–57	34–73	19–59ᵃ	2–13	23–43
Aug	2–17	7	6–23	3	24–33	1–13	3–28	3–37	2–36	4–38	1–34	4–22
Hbe	2– 6	2	1– 7	3	2– 5	5–12	17–47	4–14	5–38	30–34	18–21	16–32
Cgt	0–1?	–	–	2	0– tr	56–84	0–1?	10–86	0– tr	0– tr	–	1– 5
Bio	–	–	0– 1	–	–	0– tr	–	0– 6	0– 3	3–12	32–79	15–40
OPA	20–35	14	16–23	23	11–30	16–20	19–45	8–25	16–42	6–29	4–13	22–31
n	3	1	3	1	4	3	7	6	6	3	2	3

	Tongariro derived tephras										
	Mm	Oa-1	Oa-2	Oa-3	Oa-4	Oa-5	Oa-6	Oa-7	Oa-8	un	Rt
Opx	43–44	35–49	30	56–68	63–65	72	50–82	61	56–67	69–70	37–49
Cpx	22–30	34–47	57	29–34	32–34	25	17–44	36	31–42	27–30	39–59
Hbe	0– 1	11–16	9	tr– 1	tr– 2	3	1– 4	2	0– 1	tr– 1	3– 8
Olv	26–34	1– 4	4	3– 9	2– 3	tr	0–10	1	1– 4	1– 2	0– 8
OPA	6–13	7–32	23	8–20	9–15	9	7–12	7	2– 8	3– 6	4–14
n	3	3	1	2	3	1	3	1	4	2	3

	Egmont derived tephras												
	Eg-1	Eg-2	Eg-3	Eg-4	Eg-5	Eg-6	Eg-7	Eg-8	Eg-9	Eg-10	Eg-13	Eg-14	Eg-15
Opx	0– 2	0– 2	6	0– 2	0–16	2–35	tr– 4	7	0– 8	9	4–13	2–23	1– 7
Cpx	49–57	42–55	49	46–75	43–72	47–64	79–89	54	57–60	54	75–76	53–86	83–93
Hbe	43–49	45–58	43	25–52	28–47	17–34	11–17	39	32–43	37	12–21	12–21	6–12
Olv	tr?	–	–	–	–	–	–	–	–	–	–	0– 3?	–
Ctg	–	–	2?	–	0– 4ᵇ	tr– 1?	–	–	–	–	–	–	–
OPA	1– 5	1–11	6	4– 9	2–15	3– 4	9–11	18	7–23	12	6– 8	3–22	12–14
n	2	3	1	2	3	2	2	1	2	1	2	3	3

	Tuhua Tephra (Mayor Island)				
	1	2	3	4	5
Aeg	40	87	86	28	98
Aen	1	1?	3	2	–
Rie	4	1	3	1	–
Tuh	–	–	tr	–	–
Olv	3	2	3	1	–
Opxᶜ	6	tr	2	26	1
Cpxᵈ	29	7	3	26	1
Hbe	17	2	–	16	–
OPA	2	7	1	?	1

Hyp = hypersthene; Aug = augite; Hbe = calcic hornblende; Cgt = cummingtonite; Bio = biotite; Opx = orthopyroxene; Cpx = clinopyroxene; Aeg = aegirine; Aen = aenigmatite; Rie = riebeckite; Tuh = tuhualite. Values = % range of ferromagnesian silicate minerals (summed to 100%); tr = trace (<1%); ? = uncertain; – = not detected. OPA = % opaque minerals in 2–4φ heavy mineral fraction (by point count). n = number of samples analysed (individual analyses for specified lakes or bogs are given in Lowe 1987). Tephra abbreviations are given in Table 1.
ᵃIncludes ferrohypersthene.
ᵇCgt suggests Whakatane Ash (Wk) may be present.
ᶜMainly hypersthene; anal. 1 includes ferrohedenbergite.
ᵈExcludes aegirine; mainly augite.
Samples from Mayor I.: 1, L. Rotomanuka; 2, L. Kainui; 3, L. Maratoto; 4, L. Mangahia; 5, L. Okoroire.

sample; for example, in group 4, clinopyroxene may normally predominate over hornblende in some Egmont tephras but in others hornblende is dominant.

Some of the ferromagnesian minerals are useful as marker minerals for particular tephras or volcanic centres (Lowe et al. 1980): aegirine is diagnostic of Tuhua Tephra (Mayor Island); cummingtonite occurs as the dominant ferromagnesian mineral in Whakatane Ash and Rotoma Ash (Haroharo Complex, Okataina); biotite is dominant in Rerewhakaaitu Ash and Okareka Ash (Tarawera Complex, Okataina) (it may also amount to c. 10% in Rotorua Ash), and characteristically occurs in Puketarata Ash (Topping & Kohn 1973); olivine (forsteritic, fo_{84-87}) is found in most of the Tongariro eruptives (e.g., Mangamate Tephra), but usually in only small amounts. (Olivine may also occur in rare quantities in Mayor Island and Egmont eruptives, but is of fayalitic composition: Buck et al. 1981; Weaver in Houghton & Wilson 1986; Wallace et al. 1986.) That the distinctive peralkaline mineral assemblage associated with Tuhua Tephra contains a proportion of calcalkaline minerals in some samples (Table 5) indicates contamination of these after deposition (probably by the succeeding Egmont derived tephras, Eg-7, Eg-8?).

The mineralogical results agree closely with previous findings on pyroclastics and lavas associated with the Taupo, Okataina, and Mayor Island volcanoes (e.g., Ewart 1963, 1971; Cole 1970; Topping & Kohn 1973; Kohn & Glasby 1978; Howorth et al. 1980; Buck et al. 1981; Froggatt 1981a; Hogg & McCraw 1983; Lowe & Hogg 1986). The results are also consistent with mineralogical analyses of Tongariro and Egmont eruptives, although most published results relate to work done on near-source lavas (e.g., Clark 1960; Gow 1968; Kohn & Neall 1973; Cole 1978; Franks 1984; Cole et al. 1986; Neall & Alloway 1986; Neall et al. 1986).

Ferromagnesian mineral composition

Chemical analyses representative of most of the ferromagnesian mineral phases were obtained by EMP. A range of selected analyses is given in Lowe (1987). The analyses were undertaken (1) to confirm the optical mineralogy, and (2) to examine their potential use as an adjunct means of fingerprinting tephras (e.g., see Smith & Leeman 1982; Federman & Scheidegger 1984). Seventy-seven pyroxene grains, commonly zoned, in tephras from the Tongariro and Egmont centres, were specifically

analysed by EMP to see if these centres could be effectively separated.

The analyses, all done on grain cores, provisionally suggest some degree of separation. The Tongariro clinopyroxenes, usually colourless, project mainly as augite (mean $wo_{41.8 \pm 1.5}$; 14 analyses) in the wo-en-fs diagram. The Egmont clinopyroxenes, usually green-lemongreen to bluish green, generally contain more Ca and project as salite or high-Ca augite ($wo_{44.6 \pm 2.3}$; 38 analyses) (Lowe in press; cf. Cole et al. 1986; Wallace et al. 1986). The Tongariro orthopyroxenes (21 analyses) usually project as hypersthene (total range en_{33-69}), but the few available Egmont orthopyroxene analyses (4) show variable composition (en_{46-75}).

Egmont hornblendes were additionally examined by EMP (32 analyses), chiefly to characterise and classify the types present. Most are optically green-brown "calcic hornblendes" and, based on Leake's (1978) nomenclature and assuming all FeO (total iron) is in the Fe^{2+} form, include ferroan pargasite, pargasite, and ferroan pargasitic hornblende varieties (Lowe 1987). A second, subordinate, group of dark reddish-brown amphiboles probably comprise "oxyhornblendes" (Deer et al. 1963), and are classed as magnesio-hastingsite or magnesio-hastingsitic hornblende (assuming an Fe^{3+}: Fe^{2+} ratio of about 4:1, hence $Fe^{3+} > Al^{VI}$; Leake 1978).

Fe-Ti oxides

The Fe-Ti oxides comprise mostly titanomagnetite with rare magnetite and ilmenite, based on EMP studies. Very few grains showed exsolution features (Fig. 7A), although inclusions are relatively common (Fig. 7B). Selected analyses for some Tongariro and Egmont tephras are listed in Table 6.

Fe-Ti oxide compositions, determined in various ways, have proved useful in tephra correlation studies in New Zealand and elsewhere (e.g., Kohn 1970; Topping & Kohn 1973; Westgate & Gorton 1981; King et al. 1982; Hogg & McCraw 1983). Kohn & Neall (1973) demonstrated that Tongariro tephras could be distinguished from those of Egmont by titanomagnetite chemistry as measured by emission spectrographic analysis. The Tongariro titanomagnetites contain more Cr (especially), V, and Ni, but less Mn, than titanomagnetites from Egmont eruptives (see also Kohn 1973).

These findings are used here to attempt to distinguish Tongariro and Egmont derived tephras—the respective sources being indicated by
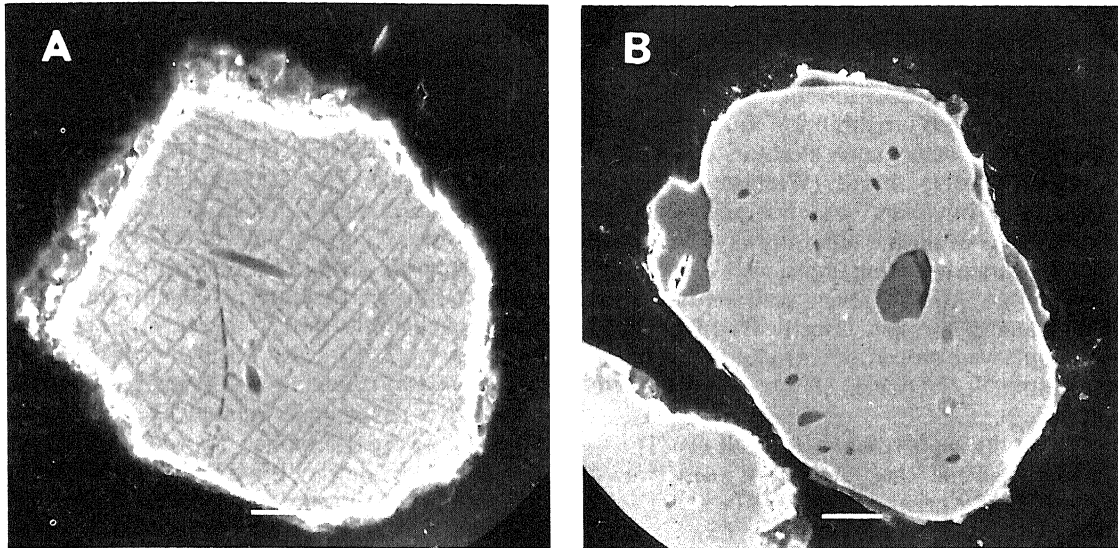
Fig. 7 A Three sets of exsolution lamellae in polished Ti-magnetite grain. (Mangamate Tephra, L. Rotomanuka.) Scale bar = 15.5 μm. B Inclusions in polished Ti-magnetite grain with a narrow glassy rim. (Mangamate Tephra, L. Rotomanuka.) Scale bar = 24 μm.

Table 6 Electron microprobe analyses of titanomagnetities in some Egmont and Tongariro tephras. Analyses recalculated using the method of Carmichael (1967).

	Egmont				Tongariro	
	Eg-4	Eg-7	Eg-9	Eg-14	Mm	Oa-8
SiO_2	0.05 (0.01)	0.06 (0.02)	0.06 (0.02)	0.09 (0.02)	0.10 (0.07)	0.15 (0.12)
TiO_2	7.81 (0.22)	9.39 (0.65)	8.64 (1.15)	9.66 (0.89)	8.00 (5.05)	12.75 (3.57)
Al_2O_3	2.85 (0.07)	2.46 (0.38)	2.99 (0.49)	3.97 (0.16)	2.68 (0.56)	2.16 (1.19)
Cr_2O_3	0.04 (0.03)	0.02 (0.02)	0.02 (0.03)	0.02 (0.02)	0.27 (0.11)	0.39 (0.17)
FeO	80.74 (0.40)	79.14 (0.91)	79.68 (0.26)	76.87 (0.76)	80.21 (4.67)	76.34 (4.10)
MnO	0.77 (0.07)	0.82 (0.08)	0.69 (0.04)	0.66 (0.05)	0.33 (0.07)	0.46 (0.16)
MgO	2.65 (0.04)	2.74 (0.19)	2.77 (0.30)	3.67 (0.36)	2.00 (0.72)	2.26 (1.59)
CaO	0.02 (0.01)	0.09 (0.17)	0.02 (0.02)	0.03 (0.05)	0.01 (0.01)	0.01 (0.01)
NiO	0.02 (0.03)	0.01 (0.02)	0.02 (0.03)	0.03 (0.03)	0.06 (0.06)	0.03 (0.03)
Total	94.95	94.73	94.89	95.00	93.66	94.55
n	10	9	7	6	5	6
Recalculated analyses						
Ulvospinel basis						
Fe_2O_3	51.95 (0.38)	49.06 (1.47)	50.04 (1.67)	47.24 (1.29)	49.96 (9.14)	41.40 (6.65)
FeO	34.00 (0.36)	34.99 (0.50)	34.65 (1.44)	34.37 (0.42)	35.25 (3.74)	39.09 (3.90)
Total	100.13 (0.52)	99.66 (0.53)	99.91 (0.36)	99.71 (0.30)	98.78 (0.84)	98.68 (1.07)
Mol%						
Usp	21.8 (5.5)	26.4 (1.9)	24.1 (3.2)	26.7 (2.3)	22.8 (13.8)	36.5 (10.3)

Analyses obtained using a 12 nA beam current at 15 kV and a 3 μm beam. n = number of analyses in mean with 1 standard deviation in parentheses. Oa-8 samples from L. Maratoto; rest from L. Rotomanuka. See Table 1 for tephra abbreviations.

the ferromagnesian mineralogy—by EMP analysis of their titanomagnetites. No attempt was made to distinguish between the individual eruptives pertaining to one or to the other of these centres. The EMP has limited capabilities for measuring elements other than major elements and certain transition or heavy metals (Westgate & Gorton 1981). Thus vanadium was not analysed, and measurements of nickel, almost always below the probe's accurate detection limits, were accordingly of little value. About 200 analyses were obtained from 18 tephra samples. Usually 10–15 grains in each sample were probed, but in samples containing very sparse Fe-Ti oxides, fewer analyses were obtainable.

The results support Kohn & Neall (1973) and generally indicate that Tongariro and Egmont eruptives may be separated using Cr (as Cr_2O_3) and Mn (MnO) abundances in particular. Cr_2O_3 always occurs in measurable quantities (c. 0.2–0.3%) in the Tongariro derived samples, but is invariably very low (usually present in trace quantitites but normally below accurate detection limits) in Egmont derived samples (<c. 0.05%). MnO concentrations in the Egmont samples (range c. 0.4 – 1.0%) usually exceed those of the Tongariro samples (c. 0.3 – 0.5%), but there is some overlap (Fig. 8; Table 6). Chemical analyses of titanomagnetites in Taranaki tephras by Franks (1984, p. 98) show broadly corroborative values: MnO concentrations average 0.8% (range 0.5 – 1.2%)and Cr_2O_3 concentrations average 0.028% (280 ppm)(range <0.01 – 0.06%). The results should be treated with caution because the differences in element concentration are small in absolute terms, and the samples show a range of values for MnO in particular. More work is required to determine if other elements may be used to discriminate between tephra sources, or between individual tephras.

Because the EMP is a grain-discrete method, mixed populations in samples may be readily detected (e.g., Kohn 1979; Westgate & Gorton 1981; Hogg & McCraw 1983). Assuming that the above differences in Cr_2O_3 and MnO concentrates in the titanomagnetites are reliable indicators of a Tongariro or Egmont source, the analyses showed that some samples may contain admixed Tongariro and Egmont derived grains. This was evident mainly in tephras deposited in the period c. 10 000 – 12 000 years ago. For example, in Fig. 8, triangles mark analyses of individual grains from a "single" tephra layer in Lake Rotomanuka that possibly contains two admixed tephras, Oa-4 and Eg-12. Ferro-

magnesian mineralogical data indicates that Oa-4 is dominant, however (Lowe 1987). Analyses from several other samples suggest that Egmont eruptives may have "dusted" the Waikato lakes between c. 13 500 and 14 500 years ago, around the same time that various tephras from other sources were being deposited (Table 1). The mixing so indicated probably arises because such concentrations of eruptions over relatively short time intervals mean that the deposits are very closely spaced in the lake sediments—hence they are potentially subject to bioturbation and other short-range mixing processes.

Analyses of suitable Fe-Ti oxide pairs enable pre-eruptive temperature estimates, and oxygen fugacities, to be determined by geothermometry (Buddington & Lindsley 1964; Spencer & Lindsley 1981). Besides their petrological and volcanological value, these parameters may be a useful aid in correlating tephras (e.g., Smith & Leeman 1982; Froggatt & Solloway 1986). Results from a limited number of Tongariro and Egmont Fe-Ti oxide pairs are given in Table 7. The Ti-magnetite/ilmenite sample pairs are assumed to have co-existed in equilibrium in the magma. Support for this equilibrium is shown by the semiparallelism of tie lines (Storey 1985) in a triangular plot of the samples' minor elements Mn, Mg, and Al + Cr (Lowe 1987).

Estimated oxide equilibrium temperatures for two pairs from the same tephra sample (Oa-4) show agreement. Other Tongariro and Egmont eruptives show a range of temperatures and oxygen fugacities (Table 7).

Light minerals

Based on XRD analysis and examination by petrological microscope, the light minerals of the 2–4ϕ fractions of tephras from the rhyolitic volcanoes comprise mainly glass (usually >c. 80 wt.%) plus small amounts of plagioclase feldspar, quartz, and rare alkali feldspar.

Tephras from the andesitic volcanoes are dominated by plagioclase feldspar (usually c. 55–85%). Plagioclase is usually the most abundant phenocryst in Tongariro and Egmont lavas (Cole et al. 1986; Neall et al. 1986). Glassy (isotropic) material makes up c. 15–45% of the tephras' light mineral fractions and is commonly vesicular and softish and fragile looking; many grains contain semi-oriented lathlike feldspar microlites. The Tongariro tephras generally contain the least glass. Many plagioclase grains have narrow glassy
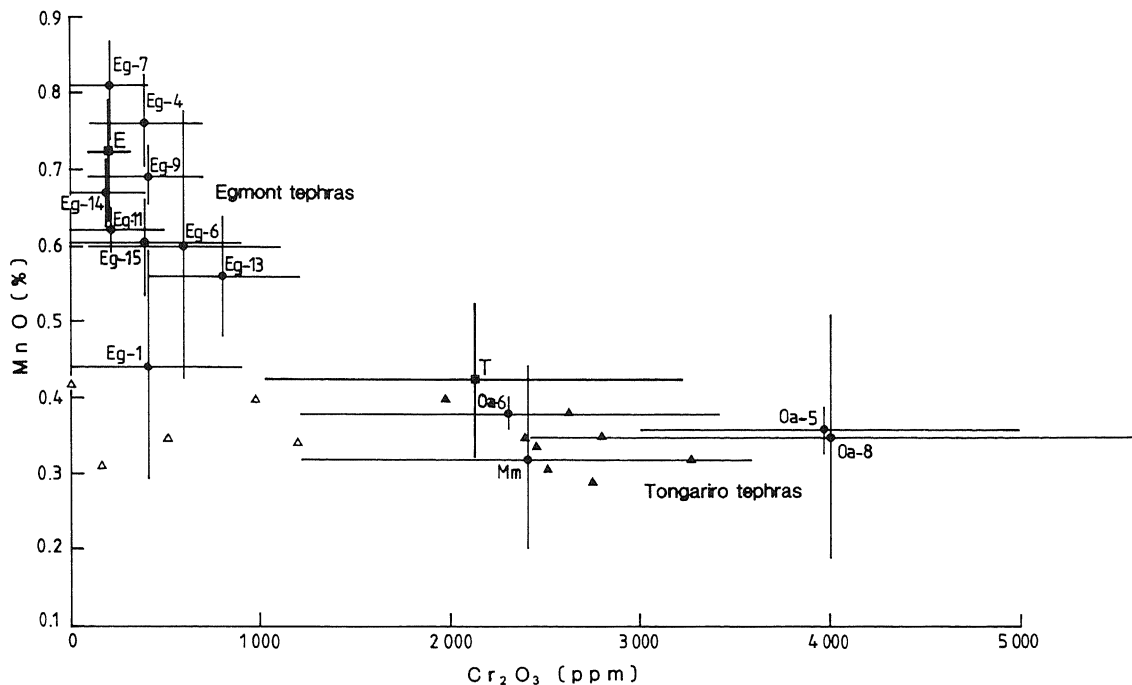
Fig. 8 MnO versus Cr_2O_3 plot for Ti-magnetites of some Egmont and Tongariro derived tephras in Lake Rotomanuka (determined by EMP). Bars represent one standard deviation from the mean. Numbers of grains analysed in Egmont tephras: Eg-1, 11; Eg-4, 10; Eg-7, 8; Eg-9, 7; Eg-11, 10; Eg-13, 12; Eg-14, 10; Eg-15, 10. Tongariro tephras: Mm, 8; Oa-5, 4; Oa-6, 3; Oa-8, 12 (abbreviations are explained in Table 1). E = mean ± 1 s.d. of Kohn & Neall's (1973) analyses (as oxides) of Egmont derived tephras younger than c. 16 000 years (n = 23); T = mean ± 1 s.d. of Kohn's (1973) analyses (as oxides) of Tongariro derived tephras younger than c. 15 000 years (n = 20). The Cr_2O_3 analyses of the Egmont tephras are approximate (see text). Triangles mark analyses of a single tephra layer in Lake Rotomanuka that possibly comprises two admixed tephras: Oa-4 (closed), Eg-12 (open).

mantles. SEM photomicrographs illustrating some of these features are given in Fig. 9A–H.

Generally, the tephric material looks fresh and unaltered, but occasionally the SEM showed evidence of incipient weathering in the form of micropits and tiny fragments ("adhering dust") on grain surfaces (e.g., Fig. 9H; cf. Heiken & Wohletz 1985). Some labradorite or bytownite grains in an Egmont derived sample had unusual tubular, "box-canyon" grooves about 1.5 – 2 μm in width. These were interpreted as biogenic by Lowe (1987). Vesicle fillings (including diatom frustules) may also occur, particularly in the andesitic scoriaceous/ pumiceous pyroclasts.

Elongated, parallel vesicles characterise many shards in samples of Tuhua Tephra.

Feldspar composition

Feldspar composition was investigated by EMP. About 130 analyses were obtained, around 90% of these being on samples of the plagioclase-rich

Tongariro and Egmont derived tephras. Mainly grain cores were probed. Six representative analyses are listed in Table 8; a fuller range is available in Lowe (1987).

The Tongariro and Egmont derived tephras show a range of plagioclase compositions, with both groups containing andesine, labradorite, and bytownite (Fig. 10). The Tongariro samples (68 analyses) range from an_{35-85} with the mean of all analyses being $an_{61 \pm 8}$; Egmont samples (49 analyses) are similar, having a range of an_{33-81} and a mean of $an_{57 \pm 9}$ (Lowe 1987). These results are in close agreement with the findings of Cole et al. (1986) and Neall et al. (1986) for Tongariro and Egmont lavas, respectively.

The few analyses obtained on the tephras derived from rhyolitic sources indicate that the feldspars are generally much less calcic. The Taupo and Okataina derived tephras usually contain oligoclase and andesine (an_{23-38}; Lowe 1986b, p .297) (cf.

Table 7   Electron microprobe analyses of co-existing titanomagnetite-ilmenite pairs, recalculated after Carmichael (1967). Oxide equilibrium temperatures and oxygen fugacities deduced from curves of Spencer & Lindsley (1981) as modified by Anderson & Lindsley (1985), using a computer programme written by J. C. Stormer.

	Egmont tephras		Tongariro tephras				
Sample	Eg-2	Eg-13	Mm	Oa-4	Oa-4	Oa-5	Oa-8
Spinel phase							
SiO_2	0.04	0.08	0.09	0.08	0.16	0.05	0.09
TiO_2	7.97	11.09	4.89	13.13	13.23	13.72	18.01
Al_2O_3	2.14	4.00	2.28	2.35	2.35	2.77	1.16
Cr_2O_3	0.04	0.00	0.30	0.24	0.26	0.37	0.28
Fe_2O_3	52.43	44.49	55.39	40.89	40.98	40.31	32.71
FeO	34.68	35.88	33.16	39.90	40.30	39.78	43.66
MnO	1.11	0.63	0.28	0.34	0.38	0.40	0.50
MgO	2.06	3.62	1.25	2.05	2.08	2.66	2.29
CaO	0.02	0.00	0.02	0.03	0.00	0.02	0.01
NiO	0.04	0.00	0.00	0.05	0.00	0.10	0.01
Total	100.53	99.78	97.66	99.06	99.75	100.16	98.71
Mol%							
Usp	22.3	30.6	14.5	37.1	37.4	37.9	51.0
Rhombohedral phase							
SiO_2	0.02	0.04	0.08	0.01	0.04	0.05	0.02
TiO_2	30.52	35.74	21.24	44.41	44.62	33.81	37.71
Al_2O_3	0.48	0.46	1.49	0.41	0.36	0.54	0.60
Cr_2O_3	0.08	0.26	0.23	0.08	0.13	0.03	0.14
Fe_2O_3	42.21	32.00	59.77	19.24	17.55	36.90	29.13
FeO	24.07	30.51	14.54	30.31	33.78	25.55	26.59
MnO	0.51	0.18	0.57	0.34	0.28	0.21	0.17
MgO	1.46	0.84	2.29	5.17	3.42	2.60	4.00
CaO	0.13	0.00	0.00	0.04	0.00	0.00	0.01
NiO	0.11	0.00	0.00	0.04	0.01	0.07	0.03
Total	99.58	100.04	100.20	100.03	100.19	99.76	98.40
Mol%							
R_2O_3	41.4	31.6	59.4	18.4	17.0	35.8	28.6
Temp.(°C)	934	948	974	917	908	1020	1095
log fO_2	−9.27	−9.62	−8.06	−10.80	−11.04	−8.84	−8.68

Oa–8 sample from L. Maratoto; rest from L. Rotomanuka. See Table 1 for tephra abbreviations.

Ewart 1969; Cole & Nairn 1975). The peralkaline Mayor Island derived Tuhua Tephra contains alkali feldspar, both sanidine (or_{53-73}) and anorthoclase (or_{35}) (cf. Ewart et al. 1968b; Buck et al. 1981; Hogg & McCraw 1983; Houghton & Wilson 1986).

Major element analysis of glass

The suitability of the EMP for analysing glass for the characterisation and correlation of tephras has been well documented since the early work by Smith & Westgate (1969) and others (e.g., see Federman & Carey 1980; Froggatt 1983; Sarna-Wojcicki et al. 1984; Davis 1985; Reasoner & Healy 1986). For several reasons, the method was seen to be potentially very useful for studying the tephras in this project. Firstly, the tephras in the Waikato region derive from multiple sources, and thus were likely to show a range of chemically distinct units. Where glass major element compositions proved too similar to distinguish one tephra from another, the continuous cores would enable them to be distinguished stratigraphically. Secondly, glass is the main constituent in the rhyolitic tephras and is easily separated. Thirdly, the EMP provides the only means of detecting and potentially correlating any distal deposits present as sparse glass shards only.

Accordingly, glass was analysed by EMP for nine elements using methods and conditions described by Froggatt & Gosson (1982) and Froggatt (1983). These included using an 8 nA beam at 15 kV, usually defocussed to 10 μm but occasionally to 20 μm, to minimise loss of Na and K. These last two elements were always analysed first

Table 8 Some representative electron microprobe analyses* of plagioclase feldspars in andesitic tephras from Waikato lakes.

	Andesine		Labradorite			Bytownite
	Eg-2	Eg-7	Eg-14	Eg-9	Oa-8	Eg-14
SiO_2	57.15	54.86	53.07	50.86	50.50	46.94
Al_2O_3	27.07	26.91	28.94	30.73	30.22	33.13
TiO_2	0.04	0.04	–	0.04	0.07	–
FeO†	0.41	0.62	0.56	0.52	0.61	0.53
MgO	0.02	0.17	0.08	0.04	0.08	0.03
CaO	9.45	9.91	11.82	13.71	14.07	16.54
Na_2O	5.98	5.64	4.76	3.86	3.45	2.10
K_2O	0.36	0.51	0.37	0.20	0.13	0.12
Total	100.48	99.66	99.60	99.96	99.13	99.39

Cations on the basis of 8 oxygens

Si	2.558	2.514	2.421	2.323	2.326	2.174
Al	1.428	1.454	1.556	1.654	1.641	1.808
Ti	0.002	0.002	–	0.001	0.002	–
Fe	0.015	0.024	0.021	0.020	0.024	0.020
Mg	0.001	0.011	0.006	0.003	0.005	0.002
Ca	0.454	0.486	0.578	0.671	0.695	0.821
Na	0.519	0.501	0.421	0.342	0.308	0.188
K	0.021	0.030	0.022	0.012	0.007	0.007
Total	4.998	5.022	5.025	5.026	5.009	5.020

*Analyses on grain cores made using a 12 nA beam at 15 kV defocussed to 10 μm. Or-1A (orthoclase) standard was used regularly to check probe calibration. – = not detected.
†Total Fe as FeO.
Sample Eg-14 from L. Rotomanuka; rest from L. Maratoto. Tephra abbreviations given in Table 1.

and second, respectively. Peak searches were carried out regularly, and glass and elemental standards were frequently analysed to check and correct for machine drift. (Glass standards used were: KN-18, comenditic glass; VG-99, basaltic glass; VG-568, Yellowstone rhyolitic glass.) Froggatt (1982a, 1983) has demonstrated that the EMP technique has good reproducibility. Duplicate analyses on three glass shards from Mapara Tephra are given in Table 9.

Around 350 individual analyses were made, some 300 of these being on glass from the rhyolitic tephras. Only about 50 reliable analyses were obtained on glass in tephras from the andesitic sources—the sparseness of suitable glass in these samples, its high vesicularity and sometimes quasifragmented nature (e.g., Fig. 9E, F), plus the presence of microlites, made it difficult to probe. Occasionally, glass rims on plagioclase grains were probed. Usually a minimum of 10–12 analyses (each on an individual shard) were obtained for each of the rhyolitic tephras present. However, for the reasons

noted above, the andesitic eruptives are less well represented, and only one or two analyses per sample were sometimes obtainable.

Representative analyses are listed in Table 10. The results are consistent with previous work on eruptives from the source volcanoes, although relatively few analyses on glass (as distinct from whole rock) have been published (cf. Ewart 1963; Ewart et al. 1968a, b; Cole & Nairn 1975; Neall 1977; Kohn 1979; Froggatt 1983; Froggatt & Solloway 1986; Houghton & Wilson 1986). Taking into account the inherent variability normally associated with the EMP analysis of Na_2O, K_2O, and SiO_2 in particular (Smith & Westgate 1969), the glass populations of most of the rhyolitic tephras are relatively homogenous, as indicated by the generally low standard deviations (Table 10), hence unmixed. Thin tephras deposited just before or just after the thicker rhyolitic deposits may contain a "background" scatter of identifiable glass shards derived from the rhyolitic tephras, probably the result of bioturbation.
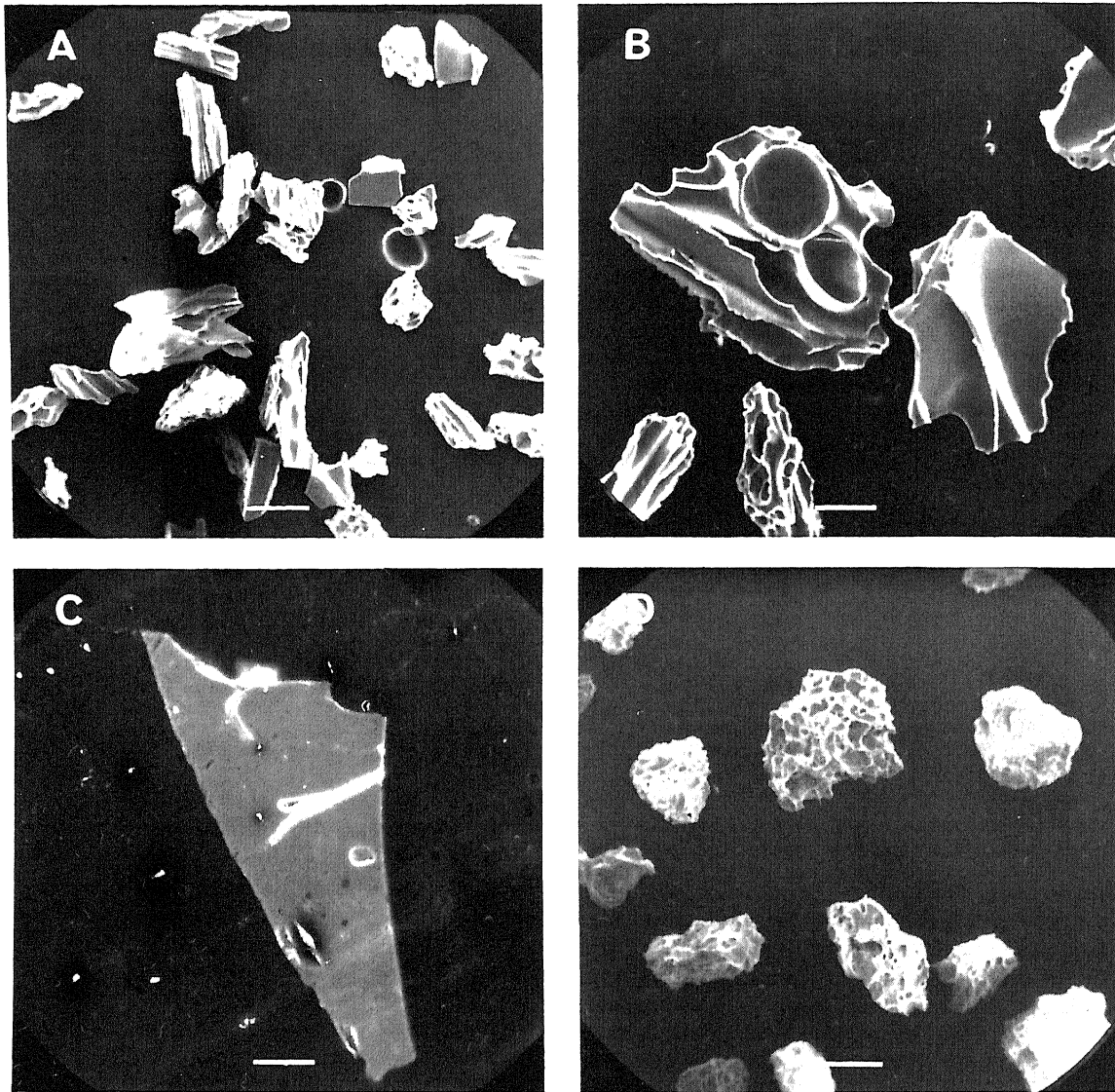
Fig. 9   A Pumiceous, platy, and cuspate rhyolitic glass shards with varying degrees of vesicularity (cf. Nelson et al. 1985); some show elongated, parallel vesicles. (Taupo Pumice, L. Rotomanuka.) Scale bar = 150 μm. B Cuspate and vesicular rhyolitic pumice shards (Taupo Pumice, L. Rotomanuka.) Scale bar = 60 μm. C Platy, rhyolitic shard (polished) of peralkaline composition. (Unnamed Mayor Island derived tephra, L. Rotomanuka.) Scale bar = 50 μm. D Blocky, andesitic pumiceous/scoriaceous glass shards. (Okupata Tephra, Oa-8, L. Maratoto.) Scale bar = 134 μm.

The Tongariro glasses (mean of all analyses SiO_2 = 61 ± 2%) can be classed as andesitic (Lowe 1987). The Egmont glasses are noticeably more silicic (mean of all analyses SiO_2 = 70 ± 2%), hence are rhyolitic-dacitic, but otherwise chemically resemble andesitic glass; they have generally high K_2O contents (mean of all analyses 4.32 ± 0.76%).

Parker's Index (P.I.) values (Parker 1970) for mean glass analyses from the tephras derived from each volcanic centre are as follows: Taupo, 64.0; Okataina, 64.4; Maroa, 67.2; Mayor Island, 81.4; Tongariro, 71.8; Egmont, 81.7 (higher values generally indicate greater susceptibility to weathering). The Mayor Island glasses have a mean peralkaline index of 1.33 ± 0.1 (Table 10).
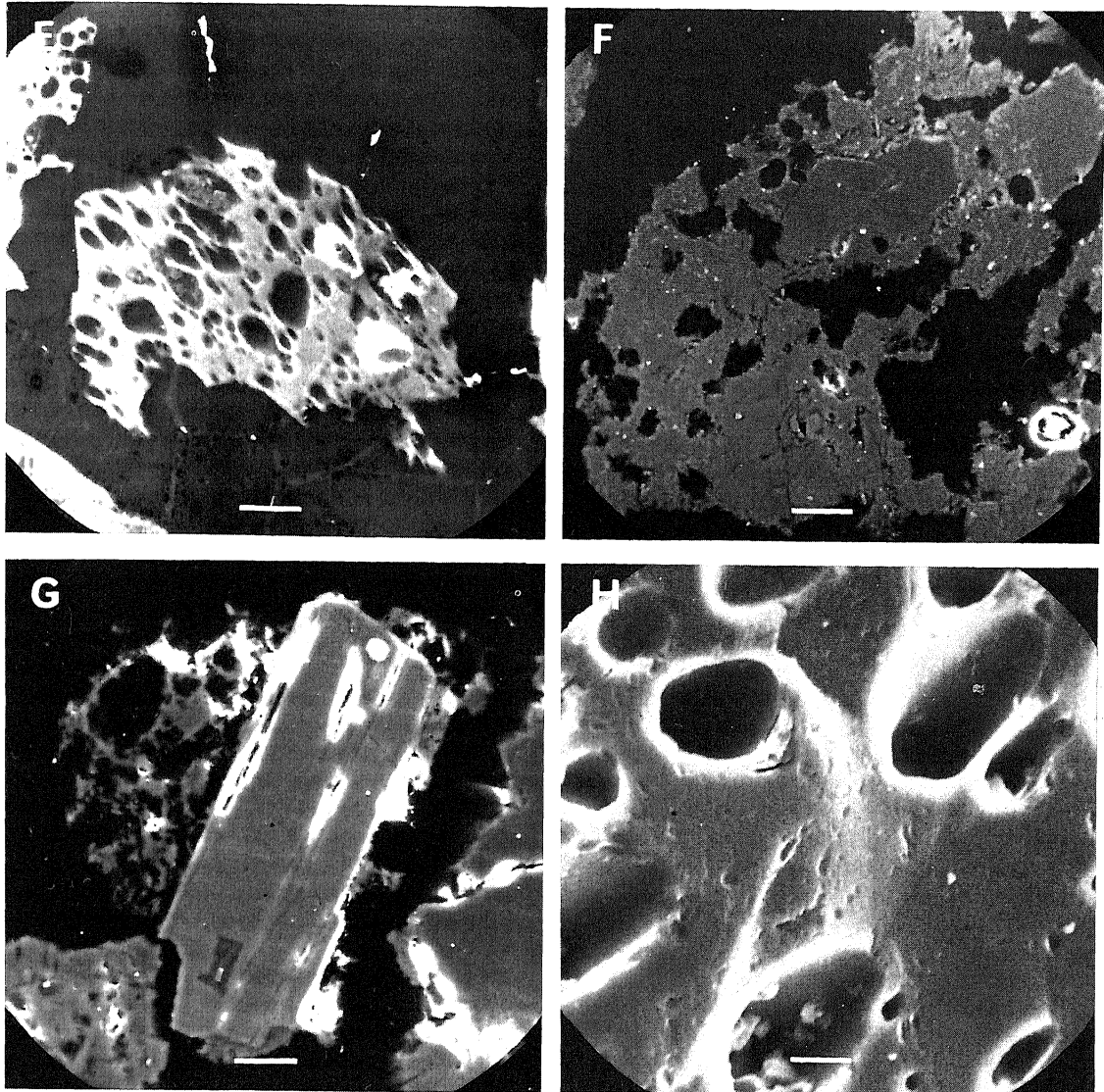
**Fig. 9**   E Highly vesicular andesitic pumiceous glass shard (polished) illustrating limited potential for probing with 10–20 μm beam. (Rotoaira Lapilli, L. Rotomanuka.) Scale bar = 33 μm.   F Vesicular, andesitic glassy material containing abundant plagioclase microlites (polished). (Okupata Tephra, Oa-1, L. Maratoto.) Scale bar = 41 μm. G Calcium rich, inclusion bearing, plagioclase grain with fragmentary, vesicular andesitic glassy rim (polished). (Eg-2 tephra, L. Kainui.) Scale bar = 24 μm.   H Surface of part of moderately vesicular rhyolitic pumice shard (peralkaline) showing surface micropitting. (Tuhua Tephra, L. Rotomanuka.) Scale bar = 8 μm.

Correlations based on glass chemistry

The analyses show that the eruptives associated with each volcanic centre can be distinguished by their major element chemistry, particularly using TiO_2, FeO*(total iron), MgO, and CaO, which typically have small standard deviations. In individual eruptives from the Okataina and Taupo Volcanic Centres, the glass major element chemistry is usually insufficient on its own to enable identification of a particular named unit. Rotorua Ash (Okataina) and Whakaipo Tephra (Taupo) appear to differ to some extent in this regard,
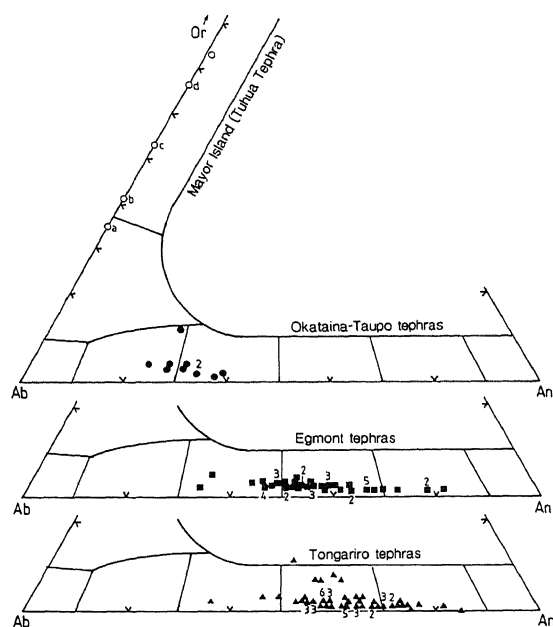
Fig. 10 Electron microprobe analyses of feldspars (mol. %). Only analyses from grain cores are plotted. Numbers indicate that two or more grains have essentially identical Ab-An-Or compositions. Analyses a–d (Tuhua Tephra) determined by R. M. Briggs (pers. comm. 1987); samples a and b were from a subaerial deposit of Tuhua Tephra on Coromandel Peninsula.

however (Lowe in press). Whakaipo Tephra, rather than Waimihia Lapilli as identified originally by Lowe et al. (1980) from its hypersthene-rich mineralogy, is re-identified here from the slightly lower concentrations of CaO and FeO* in its glass (Table 10), and from the new radiocarbon dates obtained for it (c. 2800 years old; Fig. 6). The individual Egmont tephras show some variations in glass chemisty (e.g., Eg-2 cf. Eg-12, Table 10), but such differences are statistically uncertain because of the generally high standard deviations and the low numbers of shards analysed. Variations in CaO in Tongariro (particularly) and Egmont glasses may relate in part to an effect of plagioclase microlites in the EMP analysis (cf. Reasoner & Healy 1986).

Correlations with named units can generally only be made using stratigraphic position, ^{14}C age, and other data (e.g., ferromagnesian mineralogy, abundance of feldspar) taken together.

The only eruptive from Mayor Island previously known to have reached the North Island mainland is the c. 6200 year old Tuhua Tephra (Lowe et al. 1980; Hogg & McCraw 1983). However, the occurrence of a few glass shards of peralkaline composition (Table 10; Fig. 9C) in a tephra c. 14 500 years old in Lake Rotomanuka suggests the presence of a second Mayor Island eruptive on the mainland (albeit as a very light dusting in the Waikato).

Puketarata Ash, derived from the Puketarata dome in the Maroa Volcanic Centre (Lloyd 1972; Wilson et al. 1986), is provisionally identified in the cores, mainly on the basis of its slightly unusual

Table 9   Duplicate electron microprobe analyses of three glass shards in Mapara Tephra in a core from Lake Kainui (normalised to 100% loss free).

Shard no.: analysis:	1 a	b	2 a	b	3 a	b	Mean ± 1 S.D. (n = 6)
SiO₂	77.03	77.18	76.68	76.47	76.63	76.23	76.70 ± 0.35
Al₂O₃	13.04	12.90	13.35	13.27	13.27	13.09	13.15 ± 0.17
TiO₂	0.17	0.19	0.19	0.19	0.19	0.18	0.19 ± 0.01
FeO*	1.73	1.50	1.74	1.78	1.69	1.85	1.72 ± 0.12
MgO	0.15	0.16	0.20	0.14	0.16	0.19	0.17 ± 0.02
CaO	1.24	1.20	1.30	1.29	1.25	1.47	1.29 ± 0.09
Na₂O	3.56	3.79	3.44	3.75	3.84	3.98	3.73 ± 0.20
K₂O	2.94	2.96	2.95	2.99	2.86	2.89	2.93 ± 0.05
Cl	0.14	0.12	0.13	0.12	0.11	0.13	0.13 ± 0.01
Water†	–	–	0.54	1.22	1.55	0.20	0.59 ± 0.66
Total	100.17	101.26	99.46	98.78	98.45	99.80	

*Total Fe as FeO.
†Difference between original analytical total (given) and 100.
Each shard was analysed in two different spots: a, b (see text for analytical conditions).

Table 10 Electron microprobe analyses* of glass in tephras sampled from Lakes Rotomanuka, Kainui, or Maratoto. The analyses are normalised to 100% volatile free.

Taupo derived tephras

	Tp		Mp		Wo		Hm		Op	
SiO_2	76.43	(0.64)	76.54	(0.36)	77.91	(0.26)	77.01	(0.67)	76.51	(0.40)
Al_2O_3	13.05	(0.23)	13.15	(0.17)	12.48	(0.07)	12.88	(0.33)	13.01	(0.32)
TiO_2	0.23	(0.05)	0.21	(0.04)	0.16	(0.05)	0.17	(0.03)	0.18	(0.03)
FeO†	1.81	(0.19)	1.76	(0.12)	1.52	(0.08)	1.68	(0.14)	1.73	(0.06)
MgO	0.22	(0.05)	0.19	(0.04)	0.13	(0.01)	0.16	(0.05)	0.20	(0.02)
CaO	1.31	(0.16)	1.32	(0.10)	0.98	(0.03)	1.30	(0.16)	1.41	(0.12)
Na_2O	3.97	(0.31)	3.76	(0.25)	3.62	(0.11)	3.71	(0.17)	3.86	(0.28)
K_2O	2.84	(0.17)	2.94	(0.10)	3.09	(0.10)	3.00	(0.25)	2.94	(0.13)
Cl	0.14	(0.03)	0.13	(0.02)	0.12	(0.02)	0.11	(0.03)	0.16	(0.03)
Water‡	3.21	(1.83)	1.65	(2.20)	1.55	(0.79)	1.70	(1.97)	6.33	(3.90)
n	10		9		11		20		7	

Okataina derived tephras

	Ma		Rm		Wh		Rr		Rk		Ok	
SiO_2	78.87	(0.50)	78.63	(0.16)	78.61	(0.30)	77.57	(0.58)	78.34	(0.41)	78.53	(0.47)
Al_2O_3	12.05	(0.17)	12.33	(0.10)	12.35	(0.13)	12.68	(0.32)	12.41	(0.18)	12.34	(0.08)
TiO_2	0.12	(0.02)	0.10	(0.05)	0.13	(0.03)	0.21	(0.05)	0.14	(0.04)	0.11	(0.04)
FeO	0.87	(0.07)	0.87	(0.07)	0.92	(0.08)	1.26	(0.09)	1.00	(0.13)	0.87	(0.06)
MgO	0.10	(0.02)	0.12	(0.02)	0.14	(0.01)	0.20	(0.08)	0.13	(0.03)	0.11	(0.03)
CaO	0.69	(0.10)	0.71	(0.07)	0.89	(0.04)	1.20	(0.33)	0.88	(0.07)	0.82	(0.06)
Na_2O	3.80	(0.20)	3.76	(0.06)	3.60	(0.28)	3.55	(0.29)	3.42	(0.34)	3.37	(0.26)
K_2O	3.38	(0.43)	3.37	(0.09)	3.26	(0.10)	3.19	(0.44)	3.56	(0.34)	3.71	(0.32)
Cl	0.12	(0.02)	0.11	(0.05)	0.10	(0.03)	0.14	(0.03)	0.12	(0.03)	0.14	(0.02)
Water	1.13	(1.40)	0.70	(0.43)	4.99	(3.00)	7.07	(1.71)	3.38	(2.12)	5.79	(1.66)
n	14		10		10		10		12		9	

Maroa tephra / Mayor Island derived tephras / Tongariro derived tephras

	Maroa tephra		Mayor Island derived tephras						Tongariro derived tephras					
	Pk		Tu		Tuᵃ		un		Oa-1		Oa-4		Oa-8	
SiO_2	78.49	(0.45)	75.40	(0.38)	74.74	(0.21)	75.99	(0.37)	56.18	(2.50)	62.61	(2.96)	61.78	(1.17)
Al_2O_3	12.28	(0.10)	9.43	(0.26)	9.26	(0.09)	9.68	(0.15)	20.92	(1.63)	21.19	(2.11)	16.18	(1.36)
TiO_2	0.08	(0.02)	0.29	(0.05)	0.22	(0.05)	0.19	(0.01)	0.69	(0.32)	0.40	(0.01)	0.98	(0.10)
FeO	0.90	(0.10)	5.65	(0.33)	5.64	(0.08)	4.71	(0.36)	5.28	(0.74)	1.82	(0.38)	6.41	(0.51)
MgO	0.07	(0.03)	0.02	(0.01)	0.01	(0.01)	0.01	(0.01)	2.39	(0.84)	0.39	(0.13)	2.71	(0.50)
CaO	0.64	(0.04)	0.24	(0.04)	0.20	(0.09)	0.19	(0.02)	10.19	(1.41)	7.89	(2.25)	6.44	(0.94)
Na_2O	3.23	(0.38)	4.86	(0.31)	5.51	(0.10)	4.75	(0.30)	3.42	(0.10)	3.33	(0.76)	3.52	(0.21)
K_2O	4.17	(0.48)	3.94	(0.42)	4.24	(0.11)	4.28	(0.13)	0.88	(0.37)	2.28	(0.10)	1.89	(0.23)
Cl	0.15	(0.03)	0.17	(0.06)	0.17	(0.10)	0.20	(0.01)	0.07	(0.06)	0.11	(0.01)	0.09	(0.05)
Water	5.07	(1.09)	0.73	(1.16)	1.97	(0.92)	1.87	(1.08)	2.19	(0.33)	0.63	(0.53)	1.97	(0.82)
n	12		16		7		5		2		2		10	
Peralkaline index§			1.30	(0.06)	1.47	(0.02)	1.28	(0.08)						

Egmont derived tephras

	Eg-2		Eg-6		Eg-7		Eg-11		Eg-12	
SiO_2	70.74	(0.99)	67.71	(1.65)	70.25	(2.48)	70.32	(3.83)	71.85	(0.89)
Al_2O_3	15.60	(0.52)	16.54	(1.31)	15.44	(0.85)	15.03	(1.04)	14.08	(0.38)
TiO_2	0.39	(0.07)	0.56	(0.10)	0.52	(0.07)	0.61	(0.10)	0.60	(0.10)
FeO	1.66	(0.13)	2.52	(0.40)	1.92	(0.41)	2.52	(0.80)	2.84	(0.38)
MgO	0.38	(0.14)	0.91	(0.41)	0.64	(0.53)	0.75	(0.76)	0.64	(0.13)
CaO	1.70	(0.24)	3.08	(0.97)	1.88	(1.32)	2.28	(0.62)	2.44	(0.34)
Na_2O	4.47	(0.37)	4.39	(0.37)	4.32	(0.29)	3.89	(0.99)	3.58	(0.13)
K_2O	4.88	(0.81)	4.17	(0.67)	4.85	(0.79)	4.79	(0.91)	3.84	(0.25)
Cl	0.18	(0.04)	0.12	(0.05)	0.18	(0.08)	0.14	(0.20)	0.13	(0.05)
Water	1.69	(1.09)	3.02	(1.66)	2.83	(2.47)	3.60	(1.33)	3.24	(2.61)
n	7		6		6		4		9	

*Analyses made using a 8 nA beam current at 15 kV and defocussed to 10 μm (see text).   †Total Fe as FeO.
‡Difference between original analytical total and 100.   §[Na_2O + K_2O]/Al_2O_3; mean = 1.33 ± 0.1.
n = number of analyses in mean; numbers in parentheses = 1 standard deviation.
Samples Mp, Tuᵃ (analyst P. C. Froggatt), Eg-2, Eg-7 from L. Kainui; Oa-1, Oa-8, Eg-11 from L. Maratoto; rest from L. Rotomanuka. Tephra abbreviations given in Table 1.

glass chemistry, in a sample from Lake Rotomanuka. The very low TiO_2 and MgO concentrations (Table 10) correspond to similarly low levels in residual glass of lava from Puketarata dome analysed by Ewart (1969) and Ewart et al. (1968a), and in glass from near-source Puketarata Ash (P. C. Froggatt pers. comm. 1984). Thus the deposits may be correlatives. The shards tentatively identified as representing Puketarata Ash in Lake Rotomanuka occur in a zone stratigraphically between the Rotoaira and Rerewhakaaitu tephras. An age of c. 14 000 years is suggested. This stratigraphic position and age is consistent with findings from recent mapping near the Puketarata dome (C. G. Vucetich pers. comm. 1983), although previously the stratigraphic relationship of Puketarata Ash to certain other tephras was ambiguous (see Vucetich & Pullar 1969, 1973; Topping & Kohn 1973). The postulated occurrence of Puketarata Ash in the Hamilton Basin seems remarkable, given the very small volume (0.22 km³) and subplinian nature of the deposit (Wilson et al. 1986).

TEPHRA DISTRIBUTION AND IMPLICATIONS

Distribution of rhyolitic and andesitic tephras

The relative thicknesses of rhyolitic to andesitic tephras at each lake coring site are plotted in Fig. 11. Generally, andesitic tephras are thickest in the southern part of the study region, decreasing in proportion to the thickening rhyolitic tephras to the east and southeast. For example, at Lake Rotomanuka, the andesitic material comprises c. 35% of the total thickness of the deposits and, at Lake Ngaroto, c. 36%. In Lake Okoroire, however, the andesitic component is only c. 6%, although similar numbers of andesitic tephras are present. The proportion of andesitic tephras also diminishes northwards (e.g., the andesitic tephras in Lake Kainui and Leeson's Pond account for c. 15% and c. 11%, respectively, of the total thickness of tephras in these lakes; see also Lowe 1986b, p. 291). These differences probably reflect changes in distance from the source volcanoes, and the distributional pattern of fallout (e.g., see Fig. 12).

Implications for weathering

The broad changes in the ratio of andesitic to rhyolitic material across the central Waikato region,

based on the lacustrine tephra compositions, support the findings of most studies on the subaerial tephra-derived soils—those formed from the so-called "Mairoa Ash" and "Tirau Ash" beds as described earlier (e.g., Grange 1931; Taylor 1933; Hodder & Wilson 1976; Lowe 1981a). The possible influence of this "compositional gradient" on weathering and argillisation processes in the tephra-derived soils in the central-eastern Waikato area is discussed in Lowe & Nelson (1983) and Lowe (1986b) (see also Parfitt et al. 1982b, 1983).

The P.I. values of glass in the lacustrine tephras indicate that the Egmont, Tongariro, and Mayor Island glasses (P.I.s = 71.8 – 81.7) are more susceptible to weathering than are the Maroa (P.I. = 67.2) or Taupo and Okataina derived glasses (P.I.s = 64.0 – 65.4). This implies that, in tephra studies involving detailed analysis of glass from weathering environments (e.g., Hodder & Wilson 1976), glasses from these first three centres in particular are liable to be under-represented. Similarly, olivine, which is found in small amounts in some of the Tongariro derived tephras in the lake cores, has not been recorded in any subaerial tephra deposits in the Waikato area (Lowe 1986b), presumably having been rapidly weathered in the soil-forming environment.

Isopach maps and tephra dispersal mechanisms

On the provisional isopach maps (Fig. 12), the contours are tentative because the number and geographic spread of the sites is relatively limited, and because the tephra thickness measurements may differ by small amounts in cores from the same lake (an average thickness was used in such cases). It is assumed that all of the tephric material is essentially airfall in origin (i.e., it was not overthickened, or thinned, by postdepositional wave action or by erosion from the catchment).

The outer limits of previous isopach maps (e.g., insets in Fig. 12) are generally restricted to c. 100–200 mm thickness contours. The new isopach maps presented here have improved on this degree of resolution by c. 10–100 times, and include isopachs as thin as 3–5 mm (e.g., Fig. 12B, F). The maps generally conform with the previous ones in that the more distal deposits in the Waikato region are usually thinner than the outermost contours of the earlier maps. For Rotorua Ash, the outermost isopach (c. 200 mm) of Pullar & Birrell (1973a) appears to conflict with the lake measurements (Fig. 12J, inset). The 300 mm isopach distribution pattern

Lake sites are: 1, L. Maratoto; 2, L. Rotomanuka; 3, L. Ngaroto; 4, L. Mangakaware; 5, L. Mangahia; 6, L. Rotoroa; 7, L. Rotokauri (thickness measurements do not include Rerewhakaaitu Ash); 8, L. Kainui; 9, L. Rotokaraka; 10, Leeson's Pond; 11, L. Okoroire; 12, L. Rotongata.
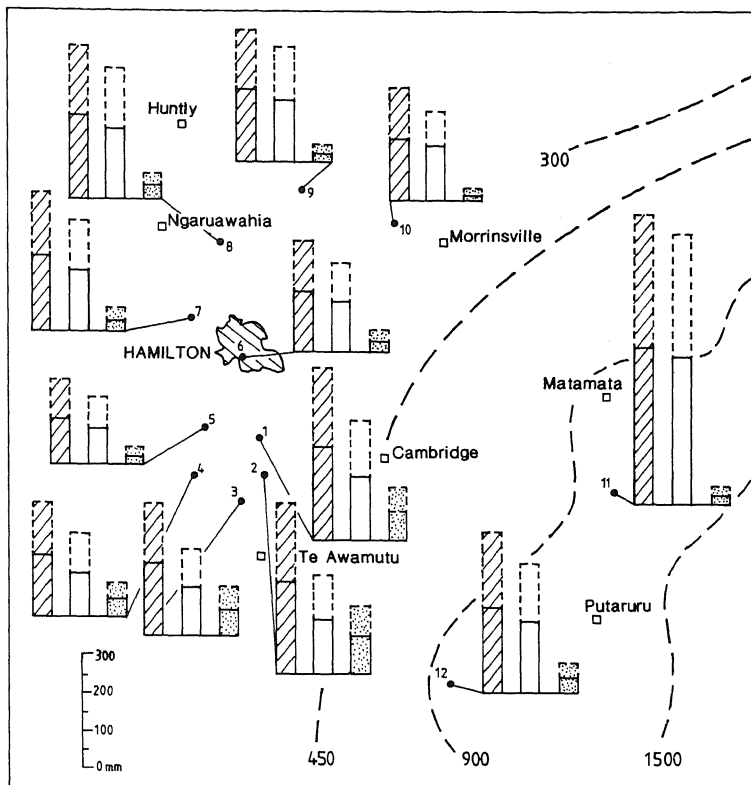

Fig. 11 Tephra thickness-compositional relationships in the Waikato area based on approximate measurements of lacustrine tephras aged ≤c. 15 000 years (i.e., younger than and including Rerewhakaaitu Ash). Bars with hatching = total thickness of tephras from all sources; blank bars = total thickness of rhyolitic tephras; stippled bars = total thickness of andesitic tephras. Solid bar lines represent actual thickness measurements; dashed bar lines represent thicknesses adjusted for compaction and dissemination to obtain an equivalent dry-land tephra thickness (see text). Dashed lines are isopach contours (in millimetres) of the sum of tephras erupted during the last c. 15 000 years, as measured at subaerial sites by Pullar (1967, p. 28).

in Fig. 12J, with a possible northwest–southeast trending fallout axis (arrowed), is more consistent with the lake data, however. In Fig. 12F (Rotoma Ash), the outermost isopach of Pullar & Birrell (1973a) of 100 mm may similarly have been overestimated (cf. approx. 55 mm dry-land equivalent thickness from lake core data).

Graphs showing isopach thicknesses plotted against distance from isopach centre for 12 tephras are given in Fig. 13. These combine the approximate thickness data from the Waikato lake cores with measurements from the previously published isopach maps as referenced in the caption to Fig. 12. The isopach thicknesses are plotted along a transect from the isopach centres towards Hamilton. These transects do not, therefore, necessarily coincide with a major or minor fallout axis (cf. Froggatt 1982b).

Near-linear semilog plots indicate an exponential decrease in tephra thickness (T) with increasing distance (x) from the source (i.e., T = ae^{-bx}; Fisher & Schmincke 1984). Various workers have suggested that a change in slope reflects a change in dispersal mechanism of the tephra, perhaps from turbulent transport near the source to normal wind dispersal of finer material further from the source. More recently, however, this flat-lying "fine tail" has been interpreted as representing co-ignimbrite ashfall rather than Plinian-type fallout material (Sparks & Walker 1977; Froggatt 1982b; Fisher & Schmincke 1984). Secondary thickening of distal tephra deposits has also been attributed to premature fallout because of particle aggregation or scavenging (Cas & Wright 1987).

Fig. 12 Provisional isopach maps for 11 tephras in the Waikato area, based on measurements from lake sediment cores (see Fig. 11 for lake names). Insets, all drawn to the same scale, allow comparison with isopachs of correlative tephras in the Taupo–Rotorua–Gisborne–Taranaki districts (B after Neall 1972; A, E after Vucetich & Pullar 1973; D, F, H, J, K after Pullar & Birrell 1973a; G, I after Topping 1973). (Eg-2 is tentatively correlated with Inglewood Tephra, map B.) All measurements are in millimetres; numbers in parentheses are thicknesses adjusted for compaction and dissemination to give an estimate of dry-land tephra thicknesses (see text). Axis-2 line and 100 mm isopach contour in map C (Tuhua Tephra) are based on Hogg & McCraw (1983). Map J (Rotorua Ash) isopach contours appear to straddle a northwest–southeast axis (indicated in inset), perhaps reflecting the effect of strong winds, a directed blast, or possibly co-ignimbrite ashfall. Pullar & Birrell (1973a) may have overestimated the thickness of Rotorua Ash in the eastern Waikato (dotted isopach; see also Fig. 13D).

A. WHAKAIPO

B. EGMONT-2 (?Inglewood)

C. TUHUA
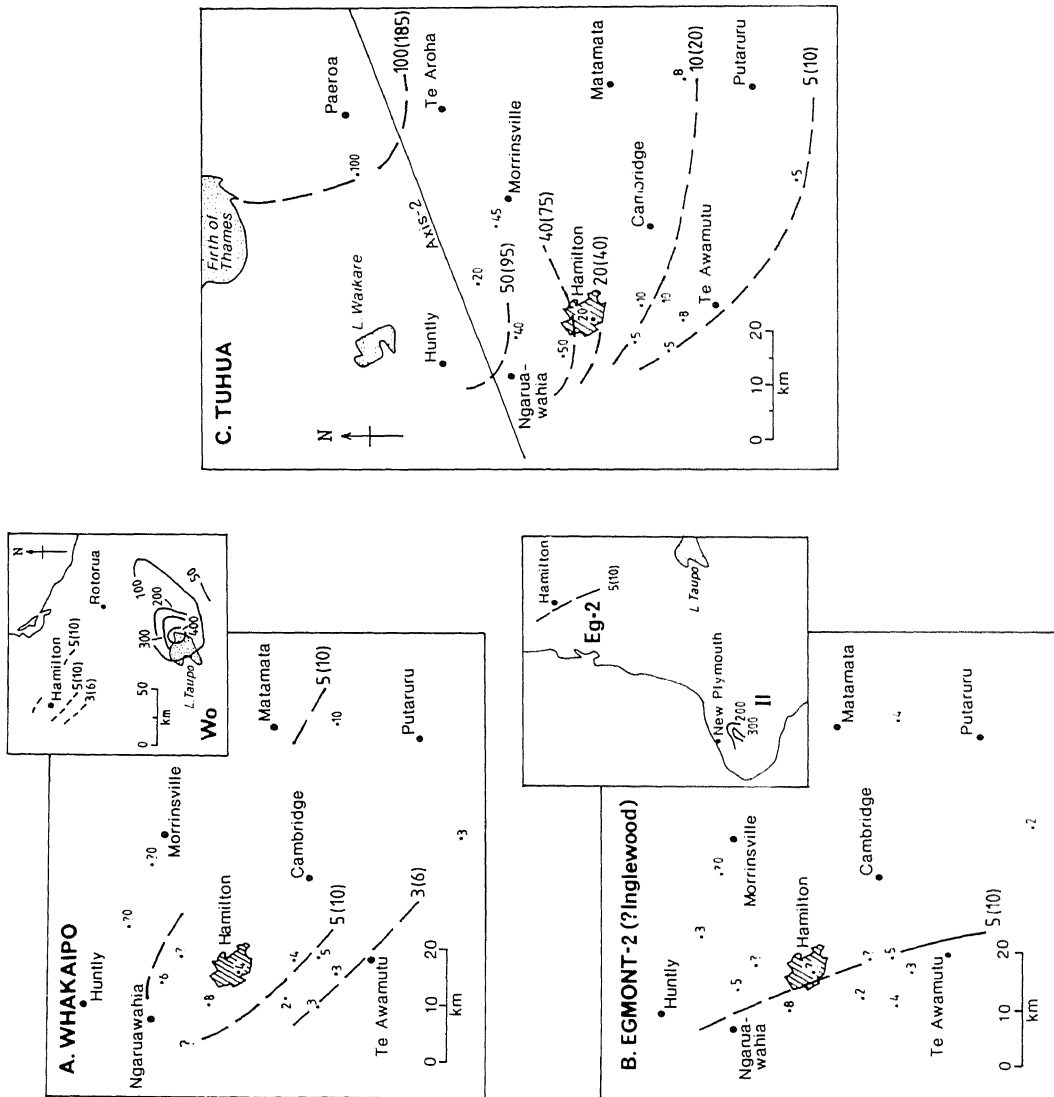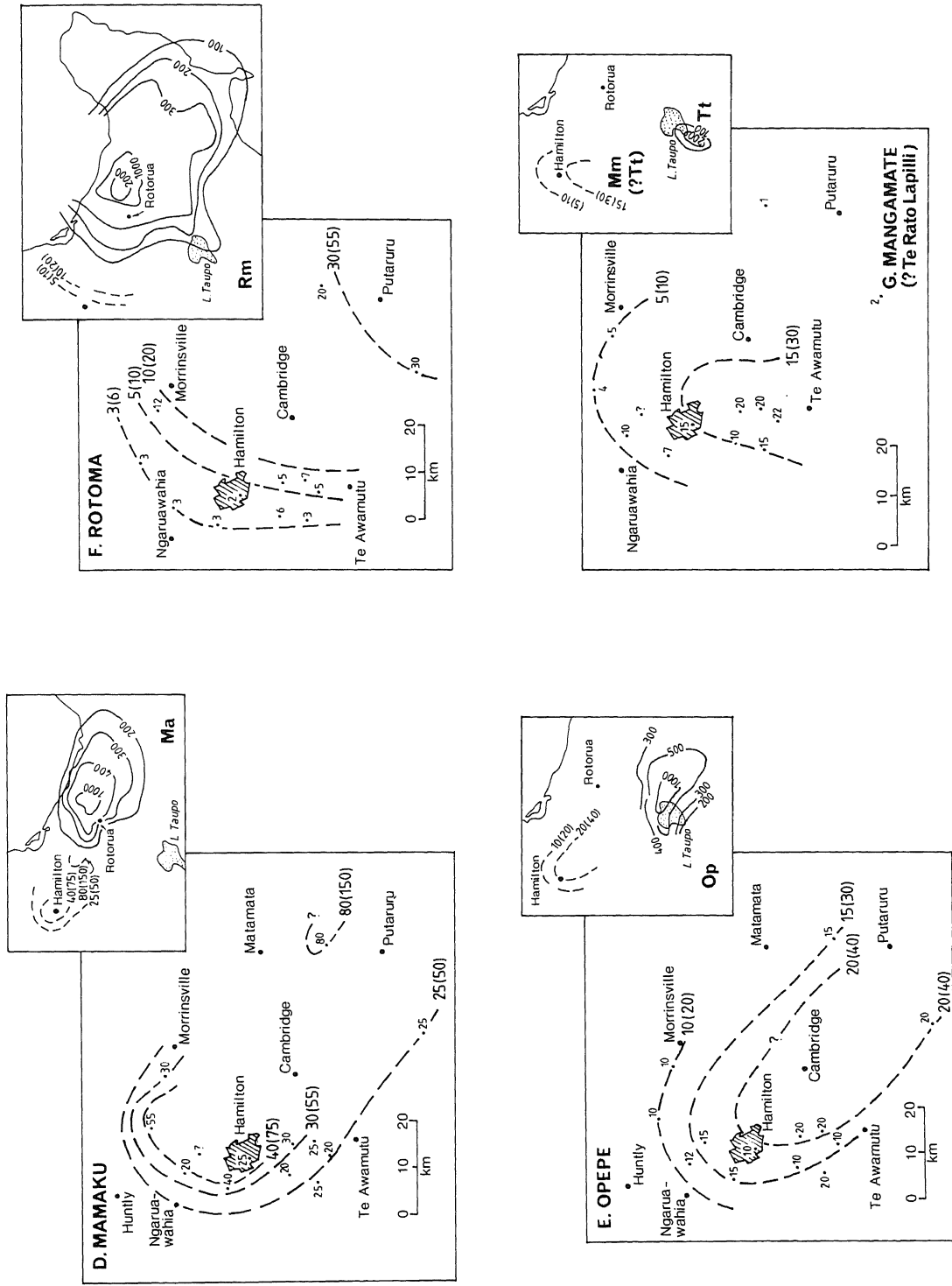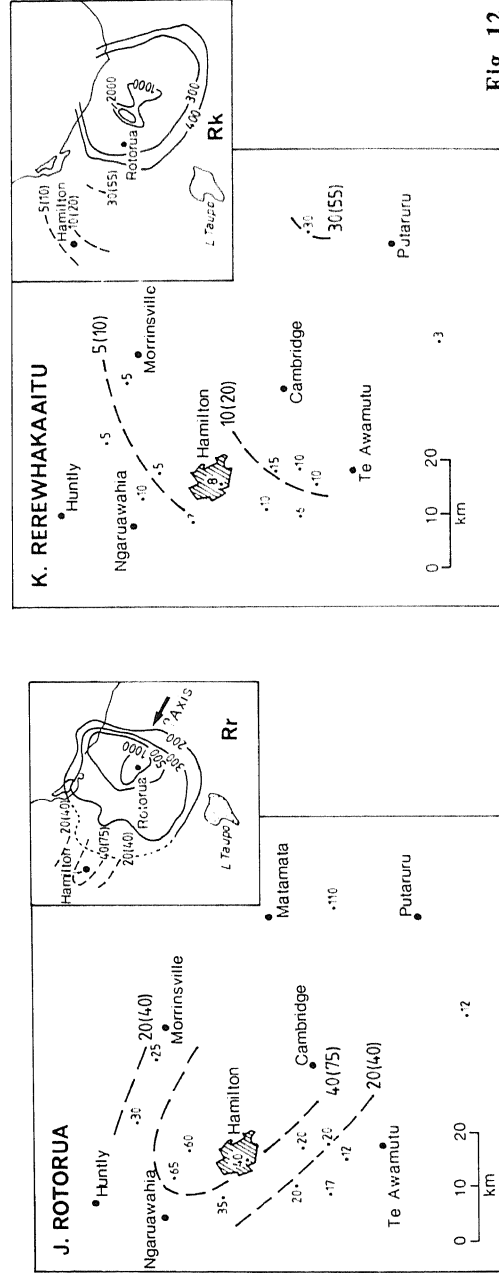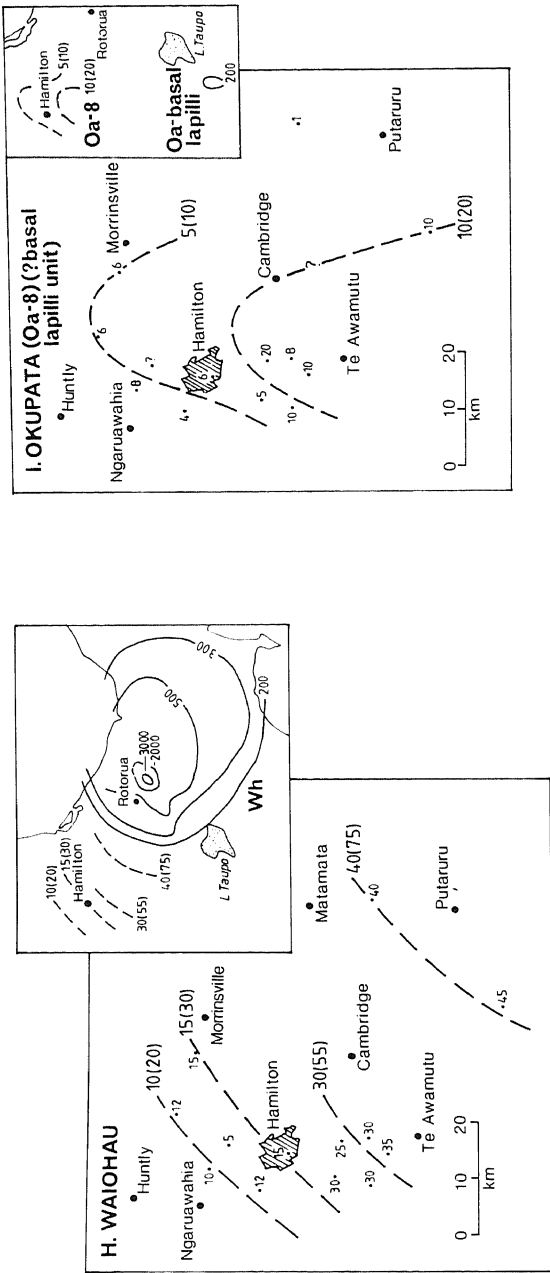
Fig. 12 (continued)

Fig. 12 *(continued)*
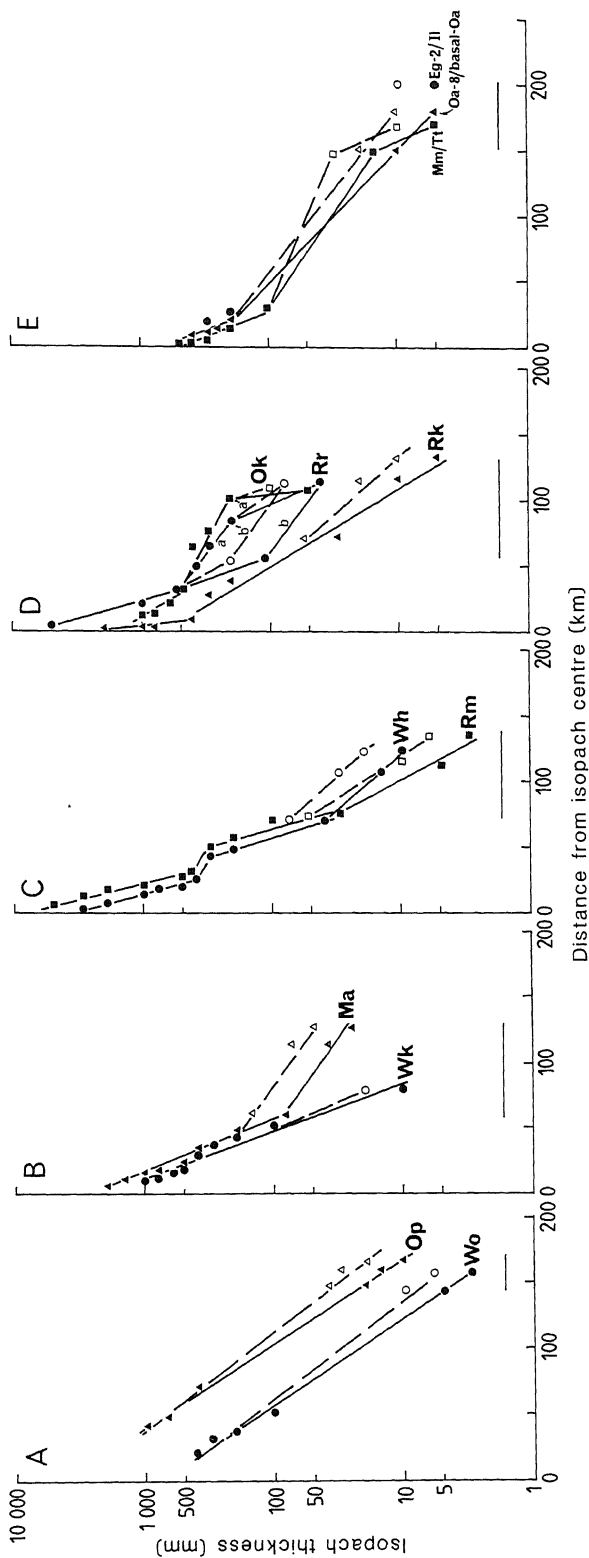
Fig. 13 Plots of isopach thickness against distance from isopach centre for 12 tephras. Dashed curves join adjusted thicknesses (open symbols) for tephras in Waikato lakes. Horizontal bars indicate region of Waikato lake core measurements. Symbols for tephras are: Wo, Whakaipo; Op, Opepe; Wk, Whakatane; Ma, Mamaku; Rm, Rotoma; Wh, Waiohau; Rr, Rotorua*; Rk, Rerewhakaaitu; Ok, Okareka; Mm/Tt, Mangamate (Waikato lakes) and possible near-source correlative, Te Rato Lapilli; Oa-8/basal-Oa, Okupata (informal unit 8, Waikato lakes) and possible near-source correlative, the basal lapilli unit of Okupata Tephra; Eg-2/Il, Egmont-2 (Waikato lakes) and possible near-source correlative, Inglewood Tephra (references given in Fig. 12).
*Curves a,a' are drawn through Pullar & Birrell's (1973a) 200–400 mm isopachs (Lake Okoroire measurement ignored); curves b,b' are drawn through the isopach based on the Lake Okoroire measurement (Pullar & Birrell's 1973a 200–400 mm isopachs ignored).

In Fig. 13, some of the plots are approximately linear (with essentially little effective difference in shape between the actual and adjusted thickness plots), and hence generally fit an exponential decay model (e.g., Fig. 13A). However, the distal fallout deposits of other tephras are thicker than the exponential would predict, most probably indicating either a change in dispersal mechanism or a contribution from co-ignimbrite ash associated with the eruptions. Mamaku Ash (Fig. 13B), Rotorua Ash, Rerewhakaaitu Ash, Okareka Ash (Fig. 13D), and possibly Waiohau Ash (Fig. 13C) show this latter pattern to a greater or lesser extent. The Mamaku and Waiohau eruptions included ignimbritic events (Nairn 1981), and Rotorua Ash local near-vent pyroclastic flow and surge events (Nairn 1980), so it is possible that the "fine tail" for these tephras in the Waikato area partly represents co-ignimbrite ash. However, a change in dispersal mechanism cannot be excluded; Nairn (1980) suggested that upper wind vectors varied during the Rotorua eruption sequence. The plots of the Tongariro derived tephras in Fig. 13E also appear to show slope breaks, but more measurements at intermediate sites are needed to corroborate this.

Tuhua Tephra (not plotted in Fig. 13) is thickest to the NNE of Hamilton City, but drops off markedly to the south (Fig. 12C). The Waikato lakes' measurements generally support the onland distribution pattern in Hogg & McCraw (1983), which shows a postulated depositional axis extending southwestwards from Mayor Island and passing to the north of Hamilton. Tuhua Tephra has recently been identified in Rotorua City, c. 5–10 mm thick (Kennedy & Froggatt 1984).

The curves in Fig. 13 suggest that many of the tephras found in the Waikato lakes are likely to persist well beyond the Waikato area. Extrapolation of the graphs indicate that for the Taupo and Okataina derived tephras, the c. 1 mm isopach is likely to occur c. 200–250 km from the source (probably c. 300 km or so for Mamaku Ash); for the andesitic tephras, the c. 1 mm isopach could occur c. 250–300 km from the source.

Possible dispersal mechanisms

The central Waikato area lies c. 70–200 km from the tephra source volcanoes, and a good proportion of the distal lacustrine tephras present relate to relatively minor deposits (in terms of thickness) near the source. Consequently, their deposition in the Waikato area must depend on certain eruption conditions or wind regimes applying.

Although the prevailing winds in the North Island are presently southwesterly–westerly (and are likely to have been so for at least the past c. 20 000 years, e.g., Salinger 1984; Stewart & Neall 1984), the predominant wind direction at altitudes greater than c. 20 km is usually easterly (Nelson et al. 1985; Buck 1985). Thus, one explanation for the deposition of many of the late Quaternary tephras in Waikato is that they derive largely from eruptions that were powerful enough to produce eruption columns exceeding c. 20 km in height (the dispersion of tephras being mainly a function of column height and the atmospheric wind regime, e.g., Walker 1981a; Wilson et al. 1978; Sarna-Wojcicki et al. 1981). This was evidently the case for the "ultraplinian" Taupo eruption (Walker 1980) and the Tuhua eruption (Buck 1985; Houghton & Wilson 1986), and possibly for the Rotorua and Hinemaiaia eruptions (Nairn 1980; Lowe 1986a), at least (see also Wilson et al. 1986). The possible role of water-magma interactions in producing very powerful (phreatomagmatic) eruptions may also be relevant (cf. Walker 1981a).

Some of the tephras may have originated from less powerful eruptions but were ejected obliquely (directed blasts) or were emplaced by strong northeasterly, southeasterly, or southwesterly lower atmosphere winds. Strong southerly winds blowing during the modest February 1975 eruption of Mt Ngauruhoe resulted in fine ash being deposited as far north as Hamilton and Tauranga Cities (Nairn & Self 1978). (Ash from this eruption has not been detected in the Waikato lakes.) The curves in Fig. 13E suggest that such winds may have been responsible for depositing Mangamate and Okupata (Oa-8) eruptives in the central Waikato lake sites (see also Topping 1973).

A number of known rhyolitic eruptives from the Taupo and Okataina volcanoes do not appear to be present as macroscopic tephras in the Waikato lakes studied: the Kaharoa* (Okataina) and the Waimihia, Motutere, Poronui, and Karapiti (Taupo) tephras. Eruptions producing two of these (Kaharoa and Waimihia) were evidently quite powerful but probably strongly controlled by contemporary winds (Pullar et al. 1977; Walker 1981b). The other eruptions were moderate to weak in nature, producing plinian or subplinian deposits (Vucetich & Pullar 1973; Froggatt 1981b, c; Froggatt & Solloway 1986; Wilson et al. 1986).

Evidently, eruptions represented by substantial deposits near the source will not necessarily persist far (nor in all directions), whereas apparently minor

deposits near the source may represent powerful sheet-forming eruptions and be widely dispersed as inconspicuous layers (see Walker 1973, 1981c; Fisher & Schmincke 1984).

TEPHRA ACCUMULATION RATE

The average rate of accumulation of tephras in the Waikato area over the last c. 17 000 years has been approximately one event per c. 400 years. Rhyolitic tephras are deposited, on average, once every c. 1100 years. Andesitic tephras are deposited more frequently, every c. 650 years on average, but in relatively concentrated bursts of activity, especially from Tongariro. Based on the average depositional rate of one event per c. 400 years, the central Waikato area can possibly expect to receive a "significant" ash fallout event (i.e., substantial enough to be recorded in the lake sediments) at any time because the last such event recorded was deposited c. 1800 years ago (Taupo Pumice). It is hard to say which volcanic centre is likely to produce this next event because all can be considered potentially active and capable of producing a widespread deposit under certain conditions (see Froggatt 1982b; Dibble & Neall 1984; Latter 1986). The Maroa Centre, with only one relatively small eruption in the past c. 17 000 years, might be considered least likely, but such a low frequency does not preclude the possibility of a large, widespread eruption in the near future. A similar comment probably applies to Mayor Island as only one major plinian tephra is known on the island (Houghton & Wilson 1986). For the reasons outlined previously, any tephra erupted from one of the six volcanic centres in question may not be carried to the Waikato area in significant quantities. However, because the lake record represents approximately 60% of the known major tephra-producing eruptions (e.g., McCraw 1975; Cole & Nairn 1975), there is perhaps a better than even

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*Kaharoa Ash probably occurs in northeastern Waikato, being tentatively identified in surficial peat deposits at three localities: the Hauraki bog (Lowe et al. 1981; Hogg & McCraw 1983); the Pohlen bog (near Matamata); and an unnamed bog in the Kaimai Range (Lowe 1987). Its apparent absence in the Lake Okoroire cores (Fig. 2) may be attributable to the difficulty of coring the very sloppy surficial lake sediments. Close inspection of all the cores taken from the other lakes has, so far, revealed no trace of Kaharoa Ash.

chance that another significant eruption from any of these volcanic centres will result in tephra fallout in the Waikato area. Such a tephra fall in Waikato, even if only a few millimetres thick, would probably severely disrupt transport and communication systems and energy and water supplies, immobilise machinery, and damage crops (Blong 1984; Dibble & Neall 1984).

TEPHROCHRONOLOGICAL APPLICATIONS TO PALEO-ENVIRONMENTAL STUDIES

The Waikato lakes are attractive for paleoenvironmental studies because: (1) most are c. 16 000–17 000 years old and hence provide a record of both late-glacial and postglacial changes in the lakes and their catchments; and (2) the dated tephras contained in their sediments provide an exceptionally detailed and, within the constraints of ^{14}C dating, accurate time-stratigraphic framework. Paleolimnological studies using the tephras as marker beds began comparatively recently and are summarised in Lowe & Green (1987). Further multidisciplinary studies are in progress.

SUMMARY

Cores from 14 Waikato lakes have provided a new record of tephra deposition in the Waikato area over the past c. 17 000 years. Forty-one distal tephras of rhyolitic or andesitic composition have been identified (Table 1). They originated from six North Island volcanic centres as follows: **Taupo**, 5 tephras (Taupo, Mapara, Whakaipo, Hinemaiaia, and Opepe); **Okataina**, 7 tephras (Whakatane, Mamaku, Rotoma, Waiohau, Rotorua, Rerewhakaaitu, and Okareka); **Maroa**, 1 tephra (Puketarata); **Mayor Island**, 2 tephras (Tuhua and uncorrelated); **Tongariro**, 11 tephras (Mangamate, Okupata [8 informal units, Oa-1 to Oa-8], uncorrelated, and Rotoaira); **Egmont**, 15 tephras (15 informal units, Eg-1 to Eg-15). These sources and correlations were distinguished using the tephras' mineralogy and composition (Table 3) together with stratigraphic position and ^{14}C chronology (Fig. 2, 6).

In terms of thickness, the rhyolitic tephras predominate at all sites, but the proportion of andesitic to rhyolitic eruptives differs across the region: c. 30–35% in the south, c. 10–15% in the

north, and c. 5% in the east (Fig. 11). The compositional variations associated with these differences may have influenced weathering and argillisation in the late Quaternary tephra derived soils in the region (Lowe 1986b).

In the Ohaupo–Hamilton area, the total thickness of the lacustrine tephras younger than c. 15 000 years is c. 25 cm (approx. equivalent to c. 47 cm on dry land); in the Whitikahu–Morrinsville area, the thickness is c. 20 cm (c. 37 cm); and near Tirau the thickness is c. 42 cm (c. 78 cm).

Provisional isopach maps are given for 11 of the tephras in the central Waikato area (Fig. 12). Isopach thickness-distance plots show some tephras to have an exponential rate of thickness decrease away from source; others have an "overthickened" fine tail possibly reflecting either a change in dispersal mechanism (e.g., strong directional surficial or high altitude winds) or the addition of co-ignimbrite ash.

The tephras preserved by the lake sediments are useful as time-stratigraphic markers in multidisciplinary paleoenvironmental studies in the Waikato area.

ACKNOWLEDGMENTS

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