

Stratigraphy and development of c. 17 000 year old Lake Maratoto, North Island, New Zealand, with some inferences about postglacial climatic change

J. D. GREEN

D. J. LOWE

School of Science
University of Waikato
Private Bag
Hamilton, New Zealand

Abstract The stratigraphy and geomorphology of Lake Maratoto and its surrounds were investigated as part of a programme of paleolimnological studies based on sediment cores from lakes in northern North Island. Changes in the lake and catchment were inferred from variations in sediment character, the correlation and timing being determined from distinctive tephra layers in the sediments and by radiocarbon dating. Nineteen new C-14 dates, on gyttja or peat, are reported (old T½, years B.P.): 11 on tephtras (Mamaku Ash 6830 ± 90, Wk227; Rotoma Ash 8370 ± 90, Wk522; 8350 ± 100, Wk523; Opepe Tephra 9370 ± 210, Wk230; Mangamate Tephra 9700 ± 140, Wk231; 10 000 ± 120, Wk232; Waiohau Ash 12 200 ± 230, Wk233; 12 500 ± 190, Wk234; 12 450 ± 200, Wk515; 12 300 ± 190, Wk516; Rotorua Ash 13 450 ± 120, Wk511); 5 on the deposition of Hinuera Formation alluvium (16 300 ± 250, Wk239; 16 900 ± 470, Wk240; 17 050 ± 200, Wk358; 16 200 +360 –340, Wk509; 15 850 ± 130, Wk510); and 3 on basal peat of the Rukuhia bog (10 250 ± 90, Wk114; 15 200 ± 130, Wk534; 10 600 ± 90, Wk553).

Lake Maratoto originated c. 17 000 years ago when a small valley was dammed by volcanogenic alluvium (Hinuera Formation). From c. 17 000 to c. 14 000 years ago the lake was about 2 m deep with clear water. Marginal peat first developed at c. 15 000 years ago, reducing the area of the lake by about one-half by c. 13 000 years ago. Lake area then expanded, possibly because of marginal erosion and/or oxidation of the peat, to its maximum size at the present day. The adjacent Rukuhia peat bog grew rapidly from c. 11 000 years ago and is now 8 m thick immediately to the west of the lake. As a result of this growth, the lake became dystrophic and deepened (3.5 m at c. 7000 years ago, 6.4 m at c. 2000 years ago, and 7.1 m today).

The developmental history suggests that net precipitation increased at c. 15 000 years ago, increased further at c. 11 000 years ago, remaining high to c. 7000 years ago at least, but with a decline at or before c. 2000 years ago. There may have been a distinctly wetter or windier period from c. 10 000 to 9000 years ago.

This interpretation is consistent with other reconstructions of postglacial climate in the Southern Hemisphere.

Keywords paleolimnology; lake sediments; drainage basins; peat; pyroclastics; tephrostratigraphy; tephrochronology; C-14; absolute age; ferromagnesian mineralogy; glass chemistry; late Quaternary; Holocene; climate; lake-level fluctuations; Hamilton Basin; Hinuera Formation; Lake Maratoto; Rukuhia; bogs

INTRODUCTION

Paleolimnology is a useful discipline for the investigation of Quaternary paleoecology and paleoclimate (e.g., Frey 1969; Birks & Birks 1980; Pennington 1981; Binford et al. 1983; Brugam 1984). Few such studies, none comprehensive, have been done in New Zealand (e.g., Deevey 1955; Kennedy et al. 1978; Boubée 1983; McGlone 1983), and hence we have begun a programme of paleolimnological studies based on sediment cores from lakes in the northern North Island.

One of the most promising areas for these studies is the Hamilton Basin (Fig. 1). Its major geomorphological features were developed in the late Quaternary, mainly by aggradation of the ancestral Waikato River (McCraw 1967; Hume et al. 1975), when a number of peat bogs and small lakes were formed. Exploratory corings of sediments on some of the lakes in 1979 verified that they are ideal sites for paleolimnological studies. The lakes are shallow with soft sediments and very low sedimentation rates. Particularly notable is a series of laterally continuous, thin, distinct volcanic ash layers. The stratigraphic sequence, thickness, lithology, and bedding characteristics of these layers is practically identical in all of the lakes examined, hence they are regarded as primary tephtras (Lowe et al. 1980) and of great value as time-stratigraphic markers. Lake Maratoto, located about 10 km south of Hamilton City (Fig. 1), was chosen as the site

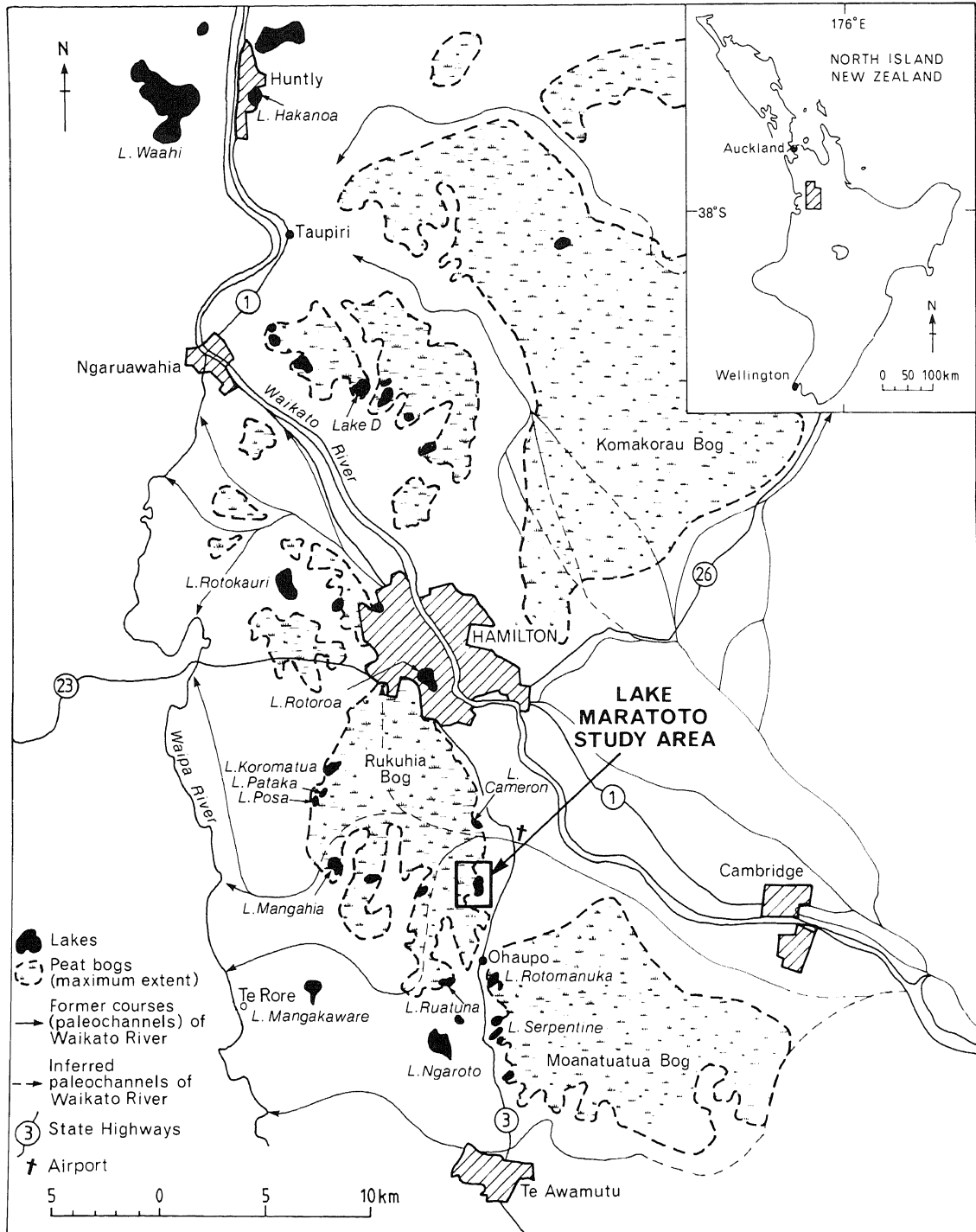


Fig. 1 The Hamilton Basin showing the location of Lake Maratoto and the distribution of other Waikato lakes, peat bogs, and the latest paleochannels of the Waikato River (after McCraw 1967).

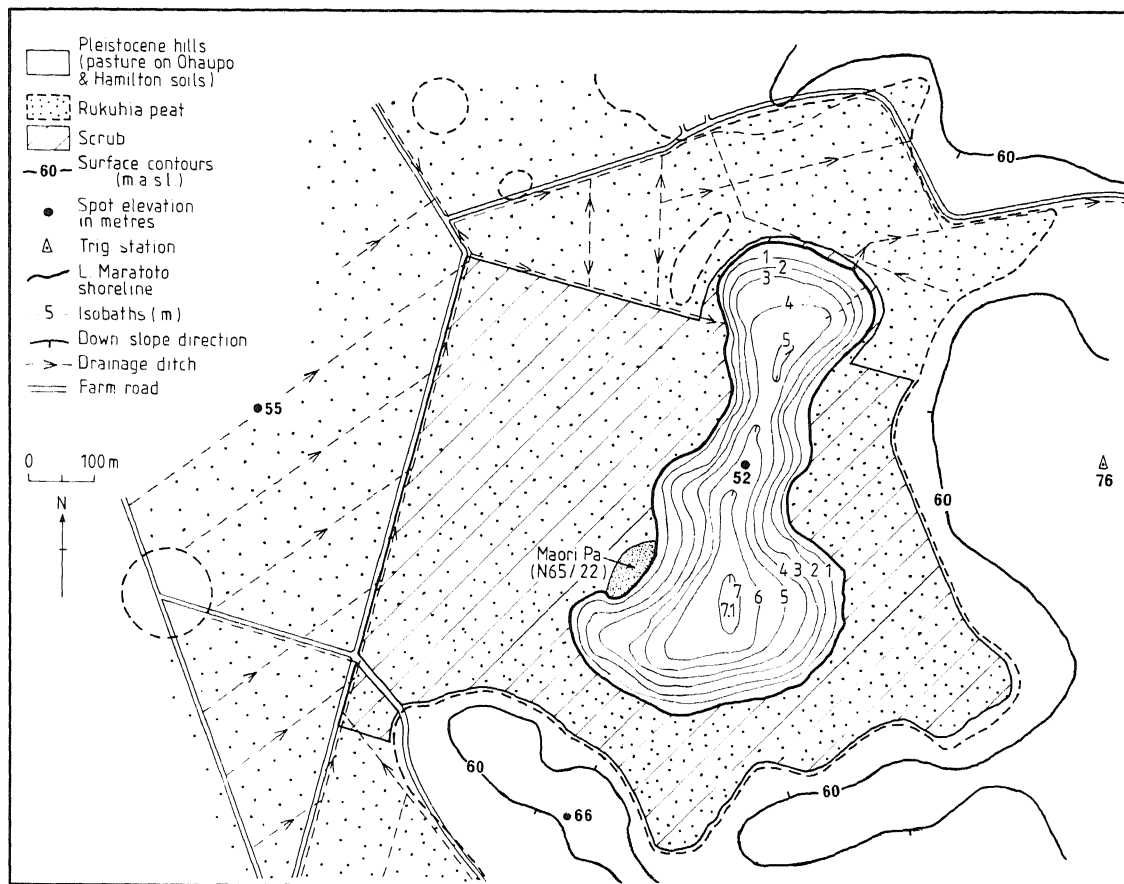


Fig. 2 The present-day Lake Maratoto area. The bathymetry is from Irwin (1982). The drainage ditches are modern, the lake having no outlet in pre-European times.

for initial paleolimnological studies. The purpose of this paper is to establish the age, origin, and developmental history of the lake basin.

Previous accounts of the origins of the lakes in the Hamilton Basin have been based on observations of lakes situated away from peat bogs (e.g., Lakes Rotokauri, Mangakaware, and Ngaroto; Fig. 1). Such lakes were formed when small valleys in low hills were blocked with alluvium (Hinuera Formation) deposited by the Waikato River at about the close of the last glaciation (McCraw 1967). Lakes on the margins of peat bogs, such as Lake Maratoto (and Lakes Cameron, Mangahia, Rotomanuka, and D; Fig. 1), are all situated within or near embayments in the hills, suggesting that they also lie in dammed valleys. However, this cannot be confirmed by observation of the local geomorphology as much of the older landscape in their vicinity is hidden by the blanket of younger peat. It is con-

ceivable that some of these lakes may have been formed by encroaching peat alone, backing up water draining from a valley (Grange et al. 1939). If the lakes did originate as valleys dammed by alluvium, it seems likely that later peat accumulation would have contributed to the form and depth of the present lake basins.

The age of the lakes is unknown, but they could have been formed at any time since the onset of deposition of the Hinuera Formation, which occurred in two phases: Hinuera-1 sedimentation (between c. 65 000 and 20 000 years ago) and Hinuera-2 sedimentation (between c. 20 000 and 12 000 years ago) (Schofield 1965; Hume et al. 1975; McGlone et al. 1978).

We have clarified the mode of origin of Lake Maratoto (and, by implication, other peat lakes in the area) by determining the topography, composition, and age of the surface lying below the lake

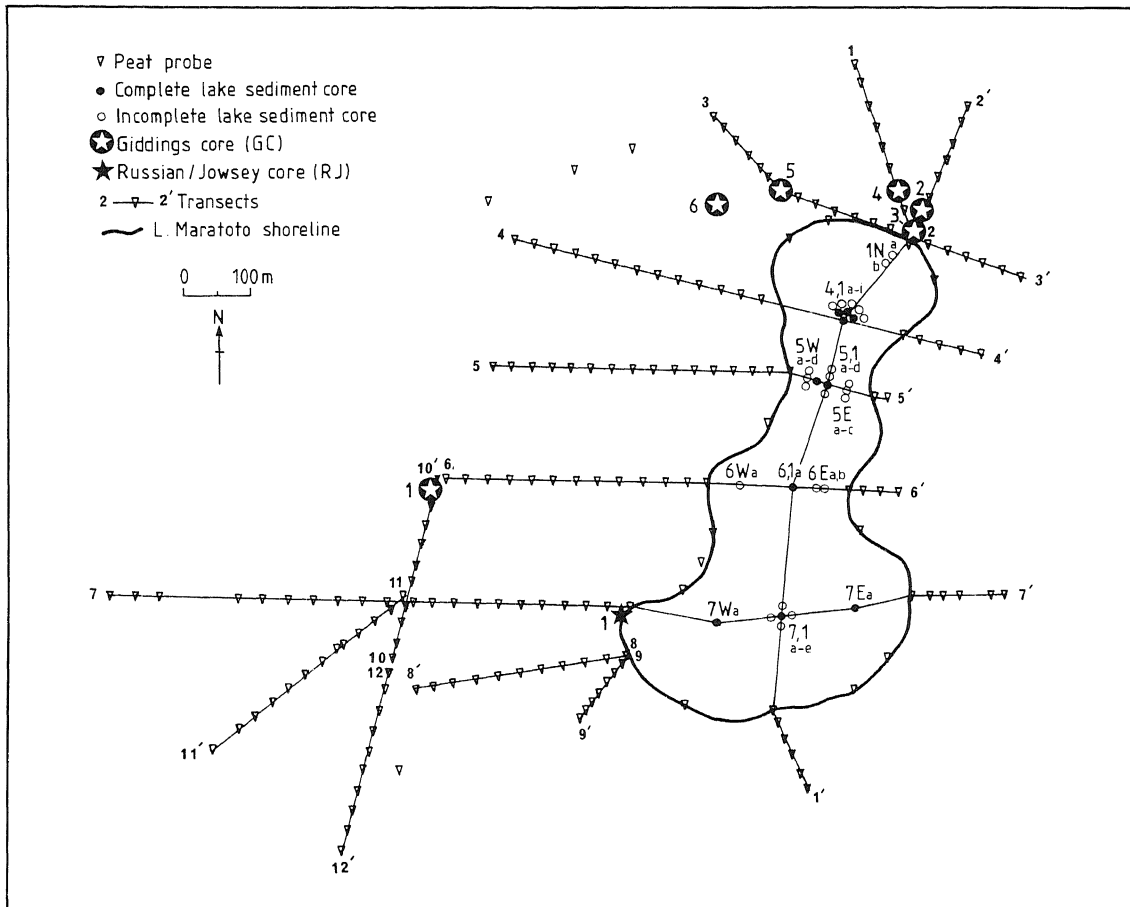


Fig. 3 Locations of transects and probing and coring sites. Lake sediment cores were labelled according to the transect they were on (a number) and their position in the lake (a letter) as follows: western cores (5W; 6W; 7W), eastern cores (5E; 6E; 7E), north cores (1N) and central cores (all on transect 1-1') (4.1; 5.1; 6.1; 7.1). The first core taken at each location was designated a (e.g., 5Wa), the second b (5Wb), and so on (see also Fig. 8).

sediments and surrounding peat. To find the age of the lake we have radiocarbon-dated the base of the lake sediments, and have estimated rates of sedimentation in the lake using the dated tephra in the sediments (Lowe et al. 1980). Utilising this tephrochronology, we also determined variations in the lake's area and depth, and the influence of peat development, from changes in the character of the lake sediment. The results have enabled us to make inferences about some aspects of postglacial climatic change.

Lake Maratoto and its surroundings

Lake Maratoto (37°53'S 175°18'E) lies on the eastern border of the domed ombrogenous Rukuhia

peat bog (23 000 ha) (Fig. 1). The lake, at an elevation of 52 m a.s.l., occupies an embayment in low hills that rise to 76 m a.s.l. immediately to the east of the lake with lower elevations to the north and south (Fig. 2). Such low hills in the Hamilton region consist of weathered Pleistocene tephra, ignimbrites, and volcanoclastic sediments that pre-date deposition of the volcanogenic Hinuera Formation (Kear & Schofield 1978). The lake is surrounded by peat, but to the west and northwest (Fig. 2) the tops of Pleistocene hills emerge above the peat, showing that the surface below is of varied relief. Some of this subpeat surface consists of Hinuera Formation sands and gravels since farm well-drilling showed "sand" 7-10 m below the present peat surface c. 400 m to the west of the lake (B. Davies pers. comm.).

The lake's bathymetry is shown in Fig. 2; its surface area is 16 ha, maximum depth 7.1 m, and volume 535 100 m³.

METHODS

Depths of peat and lake sediment were determined at regular distances along a series of transects (Fig. 3)*.

Surface contours of the peat along these transects were determined by standard levelling techniques with the lake surface (52 m a.s.l.) as the datum. Peat depths were measured, usually at 30 m intervals along the transects, with a peat probe fitted with an auger for obtaining a bottom sample. An indication of the type of substrate below the peat was obtained by (1) examining the sample in the auger screw, which sampled clays and muds, and (2) listening to sound transmitted up the probe—gravels and sands were readily identified in this way.

Lake sediment was sampled along the transects (Fig. 3) with a modified Livingstone piston corer. The coring tube was 4 m of 50 mm internal diameter PVC pipe. The lake sediment was described and classified from its colour, consistency, texture, and organic content.

To positively identify substrate types noted during peat probing, seven cores were taken through the peat and into the underlying sediments (Fig. 3). Six of the cores (GC1–GC6) were taken with a Giddings motorised hydraulic drilling rig, and one (RJ1) with a modified Russian/Jowsey D-section manual corer. The particle-size distribution of substrate samples from these cores was analysed by sieve and pipette (Folk 1968), and sand-fraction (2–4 ϕ) compositions were determined by standard methods (see Table 3). Alluvial and colluvial muds and sands beneath the lake sediments were also sampled and particle-size distributions and sand-fraction compositions were similarly determined. Ashy horizons found in the peat column, and in the lake sediment cores below Rerewhakaaitu tephra (i.e., additional to the tephra described by Lowe et al. 1980), were correlated with known tephra mainly from their ferromagnesian mineralogy; the identification of one tephra (Waiohau Ash) was confirmed by electron microprobe analysis of its glass shards (see Table 2).

Sixteen samples of the lake sediment were collected to date the major tephra layers and other significant horizons in the core (e.g., the base of the lake sediment). These samples were composites of several 1 cm thick slices of sediment taken above and below the tephra in suitable cores from throughout the lake. The tephra, identified by Lowe et al. (1980), were correlated from core to core by their distinctive colour, thickness, lithology, and stratigraphic position. (Several of the tephra identifications of Lowe et al. (1980) were

*Some of these transects have also been profiled using subsurface interface radar in a separate study by Lowe (1985, this issue), evaluating the effectiveness of the radar method for this sort of work.

Table 1 Dominant ferromagnesian mineral abundances* in Mamaku Ash, Rotoma Ash, and Waiohau Ash at Lake Maratoto.

Tephra	Sample†	Ferromagnesian silicate minerals (summed to 100%)					Opaques (vol%)‡
		Hyp	Aug	Hbe	Cgt	Bio	
Mamaku Ash	1	75	8	17	tr	0	19
	2	56	10	34	0	0	32
Rotoma Ash	3	57	29	4	10	tr	25
	4	49	27	11	13	0	8
Waiohau Ash	5	73	2	24	0	1	34
	6	52	18	27	tr	3	27
	7	58	7	31	0	4	42

*Determined by point-count of the 2–4 ϕ (250–63 μ m) size fraction of the heavy mineral assemblage (≥ 2.95 g/cm³). Between 200 and 500 grains were counted.

†1 = peat core RJ1-2; 2 = Lake Maratoto core 4,1b; 3 = Lake Maratoto core 4,1b; 4 = Lake Maratoto core 4,1f; 5 = peat core RJ1-3; 6 = Lake Maratoto core 4,1b; 7 = Lake Maratoto core 4,1d.

‡Proportion of opaque minerals (mainly titanomagnetite) in 2–4 ϕ heavy mineral fraction.

Hyp = hypersthene; Aug = augite; Hbe = calcic hornblende; Cgt = cummingtonite; Bio = biotite; tr = trace (<1%).

Table 2 Electron microprobe analyses* of glass from Mamaku Ash, Rotoma Ash, Waiohau Ash, and Rotorua Ash in peat and lake sediment cores from Lake Maratoto or Lake Rotomanuka. The analyses are presented on a normalised 100% loss free basis.

	1	2	3	4	5
SiO ₂	78.87 (0.50)	78.63 (0.16)	78.32 (0.33)	78.61 (0.30)	77.57 (0.58)
Al ₂ O ₃	12.05 (0.17)	12.33 (0.10)	12.38 (0.13)	12.35 (0.13)	12.68 (0.32)
TiO ₂	0.12 (0.02)	0.10 (0.05)	0.11 (0.05)	0.13 (0.03)	0.21 (0.05)
FeO†	0.87 (0.07)	0.87 (0.07)	0.87 (0.07)	0.92 (0.08)	1.26 (0.09)
MgO	0.10 (0.02)	0.12 (0.02)	0.10 (0.03)	0.14 (0.01)	0.20 (0.08)
CaO	0.69 (0.10)	0.71 (0.07)	0.82 (0.05)	0.89 (0.04)	1.20 (0.33)
Na ₂ O	3.80 (0.20)	3.76 (0.06)	3.55 (0.16)	3.60 (0.28)	3.55 (0.29)
K ₂ O	3.38 (0.43)	3.37 (0.09)	3.73 (0.41)	3.26 (0.10)	3.19 (0.44)
Cl	0.12 (0.02)	0.11 (0.05)	0.12 (0.01)	0.10 (0.03)	0.14 (0.03)
Water‡	1.13 (1.40)	0.70 (0.43)	3.05 (1.58)	4.99 (3.00)	7.07 (1.71)
n	14	10	11	10	10

1 = Mamaku Ash (Lake Rotomanuka, core A); 2 = Rotoma Ash (Lake Rotomanuka, core C); 3 = Waiohau Ash (peat core RJ1-3, Lake Maratoto); 4 = Waiohau Ash (Lake Rotomanuka, core A); 5 = Rotorua Ash (Lake Rotomanuka, core A).

n = number of analyses in mean (each analysis was done on a different shard); numbers in parentheses are 1 standard deviation. The location of Lake Rotomanuka is shown in Fig. 1; cores A & C were taken from near grid ref. (NZMS 260) S15/136615.

*Glass shards in the 2–4 ϕ size fractions were separated and purified using heavy liquids and Frantz electromagnetic methods, embedded in epoxy resin, polished, carbon coated, and analysed with a JEOL JXA-733 SUPERPROBE at the Analytical Facility, Victoria University of Wellington (Froggatt & Gosson 1982). All samples were analysed using an 8.0 nA beam current with either a 10 μ m or 20 μ m beam diameter, and peak counts of 3×10^5 s (measured). Repeated analysis of glass standards (KN-18 comendite glass; VG-99 basaltic glass; VG-568 rhyolite glass) gave a check on probe calibration and operation. There was probably some loss of Na and water by volatilisation (see also Froggatt 1983). Concentrations are given in oxide weight percent except Cl which is in atomic weight percent. Data are from D. J. Lowe (in prep.): "Stratigraphy, chronology, and correlation of late Quaternary rhyolitic and andesitic tephra interbedded with organic lake deposits in the Waikato region, North Island, New Zealand".

†All Fe calculated as FeO.

‡Difference between analytical total and 100.

provisional, and modifications based on new mineralogical and glass chemistry data (Table 1 and 2) are noted below.) Slices of peat 5 cm in thickness from the bottoms of cores RJ1 and GC1 were also collected. The samples were submitted for C-14 dating at the University of Waikato Radiocarbon Dating Laboratory (symbol Wk). All the dates presented and discussed in this paper are conventional and are based on the old (Libby) half-life of 5568 years (Hogg 1982).

STRATIGRAPHY

Peat and prepeat deposits

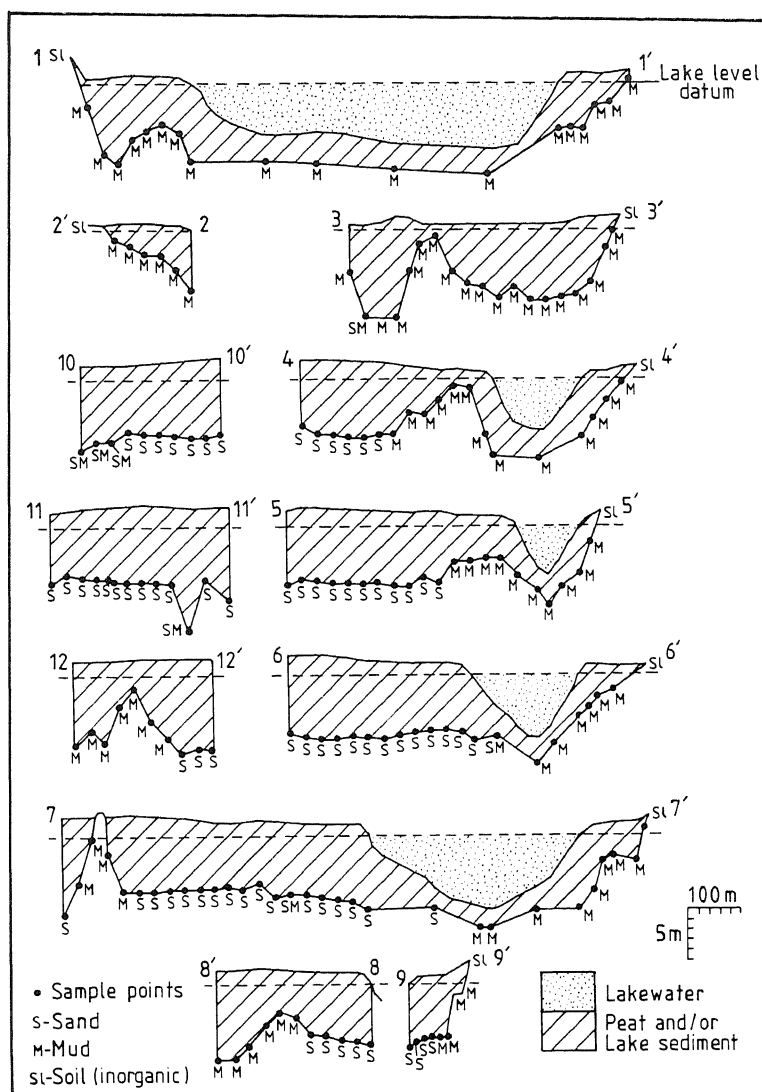
To the north and northwest of the lake (transects 1–1', 3–3', 4–4'; Fig. 4), peat depths are relatively shallow (1–4 m) and the subpeat deposits consist of greenish-blue to greyish-brown, sometimes gritty, muds. Further to the west and southwest, the peat deepens to 7–8 m and the subpeat materials are sands and gravels with a relatively flat surface (transects 5–5', 6–6', 7–7', 10–10', 11–11'; Fig. 4).

Between the lake and the hills to the east and south of the lake, the peat is less than 4 m thick. It shallows towards the hills and is underlain by muds similar to those beneath the peat to the north and west of the lake (transects 1–1', 2–2', 3–3', 4–4', 5–5', 6–6', 9–9'; Fig. 4).

Core GC1 (Fig. 5) shows that the subpeat materials to the west of the lake consist of at least 5.5 m of Hinuera Formation and are overlain by 8 m of fibrous peat. The base of the peat in GC1 has been dated (Wk553) at $10\,600 \pm 90$ years B.P. (see Fig. 9).

In core RJ1, at the southwestern lake edge, the subpeat sediments consist of a thin (10 cm) layer of greenish-grey mud passing down to sand of the Hinuera Formation (Fig. 5). There is more vertical variation in the texture of the peat in RJ1 than in GC1, but fine lake sediment is not present. Basal peat in RJ1 has been dated (Wk534) at $15\,200 \pm 130$ years B.P. Three diffuse ashy horizons, of about 10–20 mm thickness, were found in the RJ1 core. The top one (RJ1-1; Fig. 5) is identified as Taupo Pumice from its field character (vesicular, fine

Fig. 4 Transect profiles (vertical exaggeration $\times 20$) produced by combining the levelled lake sediment and peat probe depths. Lake sediment thickness was taken to be the thickness of sediment plus tephra layers between the top of the consolidated lake sediment above the Taupo tephra and the junction between the muds below the Rerewhakaaitu tephra (names and stratigraphy of the tephras are given in Fig. 8). Because of its sloppy nature, some of the sediment above the Taupo tephra was occasionally not sampled or was lost during coring, and sometimes the bottom alluvial mud layer was not quite reached. In these cases, total sediment thickness was obtained by adding estimated sediment thicknesses above the Taupo tephra and below the Rerewhakaaitu tephra. These estimates were calculated from sedimentation rates in the sediment immediately above and below these tephras respectively, provided the core included all the tephras between and including the Taupo and Rerewhakaaitu. The estimates were corroborated from sediment thicknesses in more complete nearby cores.



pumice lapilli) and persistent occurrence within a metre of the bog's surface. The middle (RJ1-2) and lowest (RJ1-3) ashy horizons both have a ferromagnesian mineralogy consistent with a source from the Okataina Volcanic Centre (Table 1; Lowe et al. 1980), and are probably Mamaku Ash and Waiohau Ash, respectively. The identification of the lowest tephra as Waiohau Ash was supported by the major element chemistry of its glass (Table 2). The only viable alternative, Rotorua Ash (c. 13 400 years), has distinctly more TiO_2 , FeO, MgO, and CaO than Waiohau Ash (Fig. 6) and hence is a less-likely correlative.

Cores GC2-5 to the north and northwest of the lake all showed similar features (Fig. 5). The peat column consists entirely of fibrous, sometimes woody, peat, occasionally with two diffuse ash layers. In GC2 these are identified as the Taupo (top) and the Mamaku tephras; in GC3 they are probably the Mamaku and Waiohau tephras. The subpeat materials consist of about 1 m of moderately weathered gritty mud (upper unit) unconformably overlying at least 3 m of strongly weathered clay (lower unit) (Fig. 5). Upper unit samples (U-1 to U-4) are texturally similar (sandy mud or sandy silt; Fig. 7A). Their grading curves (Fig. 7B) closely

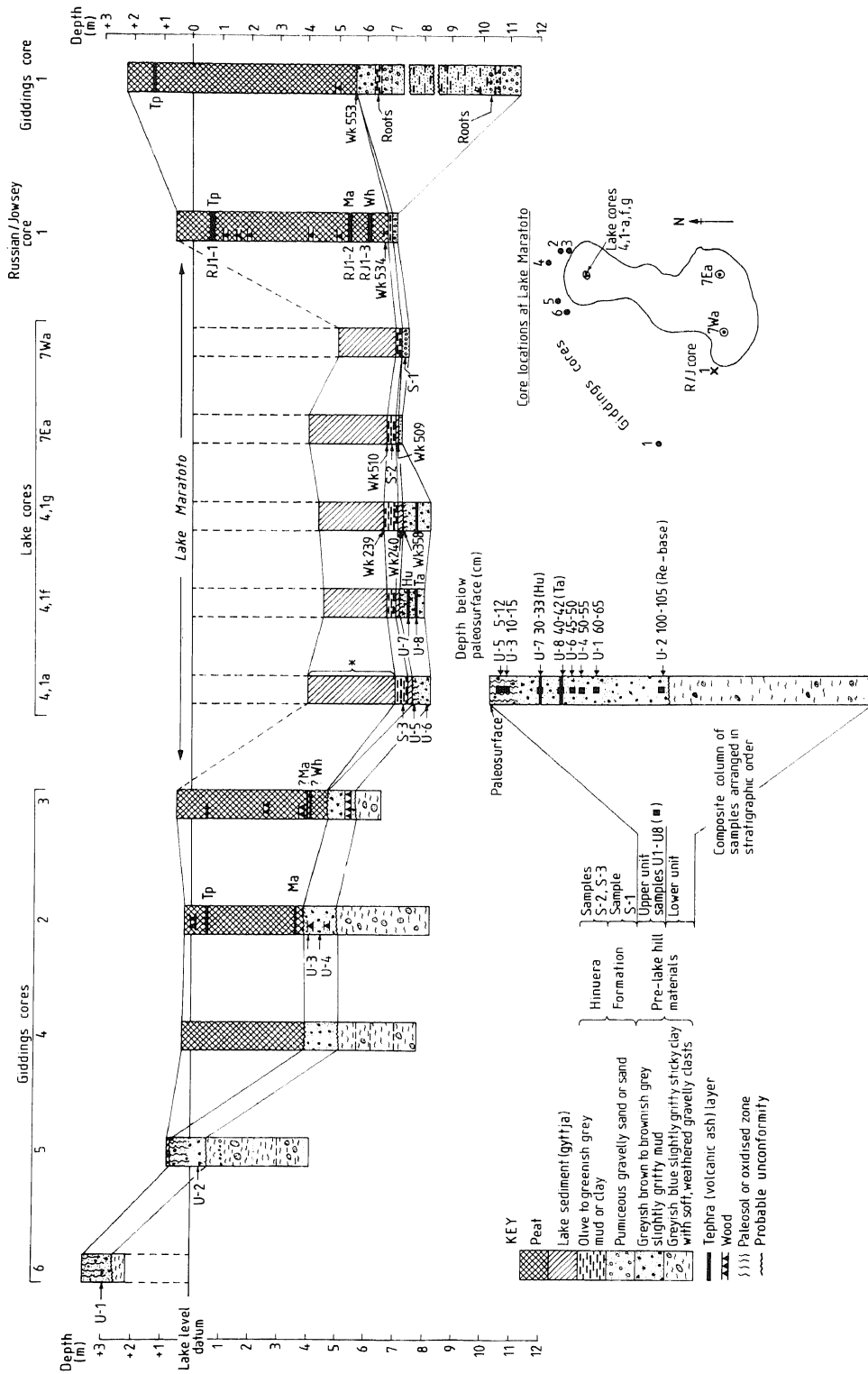


Fig. 5 Diagram showing the stratigraphy of the peat cores and correlation of the subpeat and subtytja deposits, and the positions from which samples for C-14 assay (WK) or compositional analysis (S-1 to S-3, U-1 to U-8, RJ1-1 to RJ1-3) were taken. Tephra symbols and names are: Tp, Taupo Pumice; Ma, Mamaku Ash; Wh, Waiohau Ash; Hu, Hauparu Tephra; Ta, Tahuna Tephra; Re, Rotoehu Ash.

*The teprostratigraphy of this part of the cores, based on Lowe et al. (1980), is shown in Fig. 8, and sampling positions for C-14 dates are shown in Fig. 9.

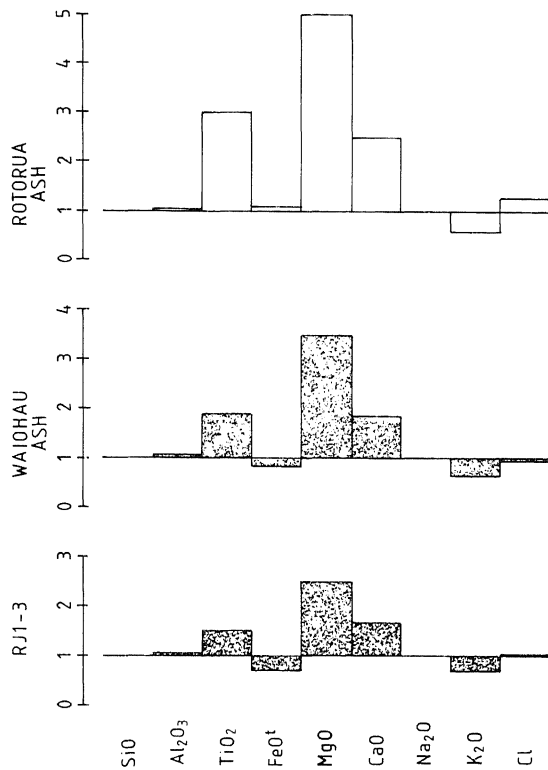


Fig. 6 Chemical composition of glass in peat core sample RJ1-3 compared with that in samples of Waiohau Ash and Rotorua Ash (data from columns 3, 4, and 5 in Table 2, respectively). The histograms are plots of ratios of element concentrations in the samples to concentrations of the same elements in Yellowstone Rhyolite Glass standard VG-568 (the method of plotting ratios is after Sarna-Wojcicki et al. 1984). RJ1-3 is better matched to Waiohau Ash, its probable correlative, than to Rotorua Ash.

match those of late Pleistocene tephra that mantle the Pleistocene hills in the area. The sand mineralogical analyses (Table 3) confirm that the upper unit consists of late Pleistocene tephra. The top part (U-3) is probably largely derived from (?)Hauparu tephra; the middle to bottom parts (U-4, U-1, and U-2) are mainly derived from (?)Tahuna tephra mixed with Rotoehu tephra (Table 3; Fig. 7D). The lower unit consists of strongly weathered materials deposited considerably before Rotoehu tephra, hence is not considered further.

Lake sediment and prelake-sediment deposits

The stratigraphy, lithology, and chronology of the cores are given in Fig. 8. Complete cores penetrated to sublake-sediment muds and sands; other

cores were incomplete but could be matched with the rest using the tephra as stratigraphic markers.

Complete cores all have an upper part consisting of 2–3 m of lake sediment (mainly dy-gyttja and gyttja, or peat in shallow-water cores) containing a series of thin (1–40 mm) tephra layers, and a lower part of either about 1 m of olive to greenish-grey fine mud (in middle and northern cores) or up to about 50 cm or less of alternating greyish-white mud and unweathered pumiceous sand layers (in cores from the southwest of the lake). The junction between the gyttja and the underlying muds and sands is taken as marking the origin of the present-day lake.

Particle-size analysis (Fig. 7A, C) of three samples (S-1 to S-3) of these subgyttja materials (sand, mud, and clay, respectively) show a fining trend eastward and northward in the lake basin (evidenced also in Fig. 8). There is thus a gradation in the subpeat and subgyttja deposits from coarse gravelly sands west of the lake at GC1, through sands at the base of RJ1 and the lake cores from the western side of the lake (cores 7W, 6W), to muds fining to clays in the eastern and northern parts of the lake. We interpret these muds and clays as a fine lithofacies of the Hinuera Formation deposited from suspension. This view is supported by the grading curves plotted in Fig. 7C that show that S-1 is similar to Hinuera lithofacies C2 (of Hume et al. 1975), while S-2 and S-3 apparently represent a finer variant of their lithofacies D. The C-14 dates straddling the Hinuera muds and clays (Wk239, 510; Wk240, 509; Fig. 9) show that these were deposited relatively rapidly between c. 16 000 and c. 17 000 years ago. This time is around that of the last stages of vigorous Hinuera-2 deposition in the Hamilton Basin (McGlone et al. 1978).

The 10 cores that penetrated beneath the Hinuera muds or sands have a thin layer (5–15 cm) of olive gyttja overlying up to 80 cm of gritty mud, usually with a dark 20 cm thick paleosol-like top containing two or three diffuse grey ashy layers (Fig. 8). We interpret the thin gyttja layer as having been deposited in a relatively short-lived proto-Lake Maratoto (see "Developmental history").

The composition of the gritty muds (samples U-5 to U-8; Fig. 5) below the proto-Lake Maratoto gyttja matches that of the subpeat upper unit materials (Fig. 7A, B, D; Table 3). Hence they are also Pleistocene hill materials and are contiguous with the subpeat materials.

All these Pleistocene hill material samples (U-1 to U-8) thus appear to consist chiefly of Hauparu, Tahuna, and Rotoehu tephra, which are aged between c. 37 000 and c. 40 000–50 000 years (Fig. 7D, 8). Neither Okareka Ash, aged between c. 17 000 and c. 20 000 years (Vucetich & Pullar 1969;

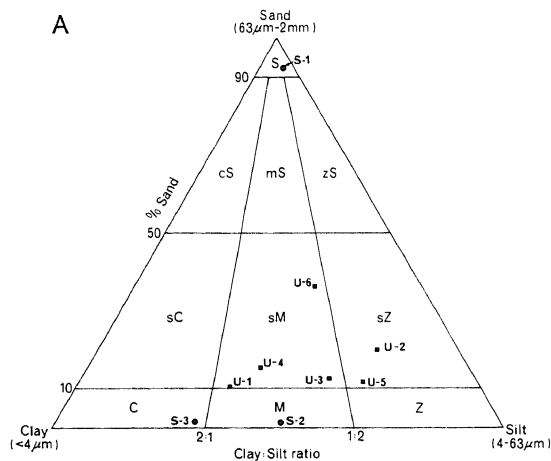
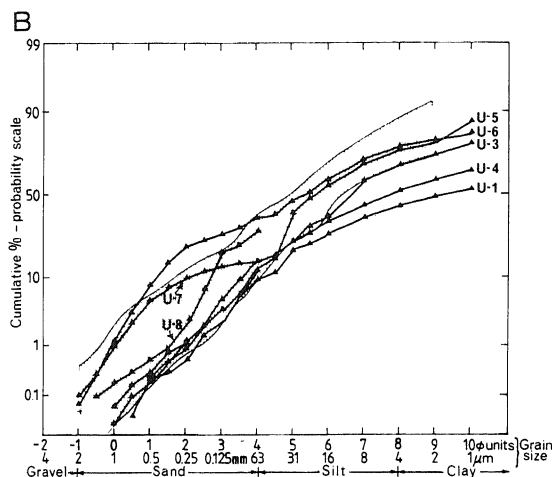


Fig. 7 Compositional analyses of the subpeat and sublake materials.

A Triangular textural plot for samples S-1 to S-3 (Hinuera Formation) and U-1 to U-6 (subpeat and subgyttja Pleistocene hill materials). Textural classes (from Folk 1968) are: S, sand; s, sandy; Z, silt; z, silty; M, mud; m, muddy; C, clay; c, clayey. Sample S-1 is a slightly gravelly sand.



B Comparison of the particle-size distributions of upper unit materials (U-1, U-3 to U-8) with those of late Pleistocene tephras from the Waikato region (stippled band). The latter Waikato samples (30) comprise tephras aged from c. 17 000 to c. 40 000–50 000 years (see Table 3; data from Lowe 1981).

Pullar et al. 1973), nor Kawakawa Tephra, aged c. 20 000 years (Vucetich & Howorth 1976a), are recognised (Table 3; Fig. 7D), although both are known to have been deposited in the region (Pullar & Birrell 1973; Lowe 1981). So it seems that there is a disconformity, possibly of up to about 20 000 years duration, between the proto-Lake Maratoto gyttja and the Pleistocene paleosurface, a suggestion supported by the moderately weathered and paleosol-like character of the paleosurface.

Lowe et al. (1980) identified the series of tephra layers above the Hinuera mud in core 4,1b. The tephras that were provisionally identified as ?Rotoma Ash and Unnamed ash by Lowe et al. (p. 483) are reidentified here as Mamaku Ash and Rotoma Ash, respectively. Mamaku Ash, dated at (Wk227) 6830 ± 90 years B.P. (Fig. 9), is characterised by its Okataina-derived ferromagnesian mineralogy (Table 1) and glass chemistry (Table 2; cf. analyses in Cole & Nairn 1975 and Kohn 1979). Rotoma Ash, with dates of (Wk522) 8370 ± 90 years B.P. and (Wk523) 8350 ± 100 years B.P. (Fig. 9), contains the diagnostic amphibole, cumingtonite (Table 1; Hogg & McCraw 1983). Its glass chemistry is listed in Table 2.

The Taupo, Tuhua, Mamaku, Opepe, Mangamate, Waiohau, Rotorua, and Rerewhakaaitu tephras were readily discernible in cores from throughout the lake (Fig. 8) and were used to calculate sedimentation rates during the lake's his-

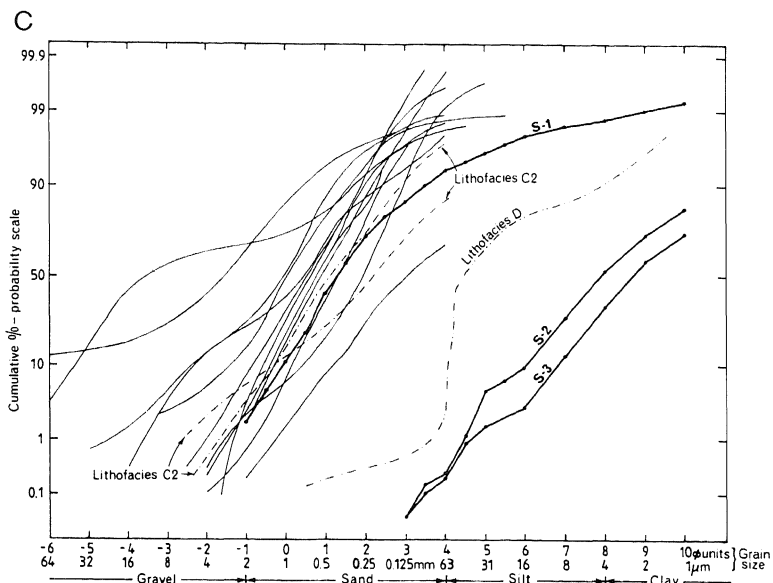
tory. Dates on gyttja associated with all these tephras, including 11 dates not published in Lowe et al. (1980), are given in Fig. 9. Dates on the gyttja above and below the Hinuera muds, and on the proto-Lake Maratoto gyttja, are given also.

The C-14 dates obtained on the tephras used as markers, apart from those for the Waiohau Ash, closely match dates on the same tephras elsewhere (Topping 1973; Pullar et al. 1973; Nairn 1980; Hogg & McCraw 1983)*. This agreement indicates that the chronology for the lake's developmental history may be regarded in large part as reliable, as the independently dated tephras provide a check on the accuracy of the radiocarbon dates (an important consideration for projected paleoecological and paleolimnological studies; Mathewes & Westgate 1980). The Waiohau Ash has been previously dated at (NZ568) $11\,250 \pm 200$ years B.P., (NZ878) $11\,100 \pm 210$ years B.P., and (NZ1135) $11\,800 \pm 150$ years B.P. (Pullar & Heine 1971) and has a generally accepted age of c. 11 300 years (Pul-

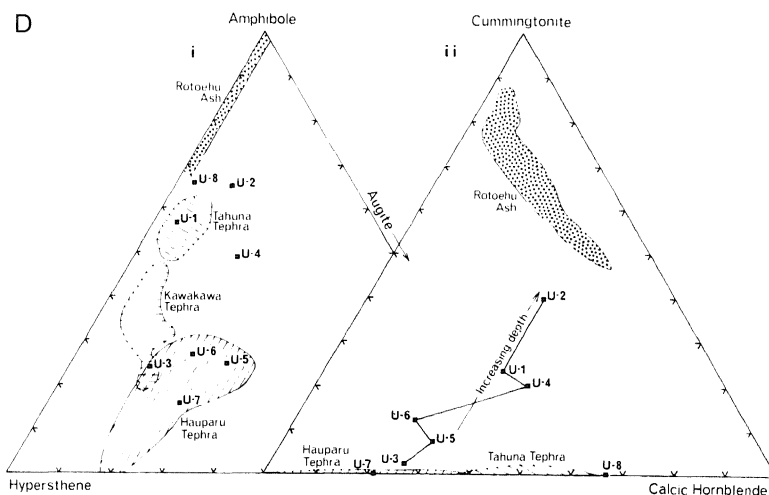
*The dates obtained on Rotoma Ash (which was not used as a stratigraphic marker) differ markedly from previous age estimates of c. 7000–7300 years by Pullar & Heine (1971) and Pullar et al. (1973), but are better matched with the date of (NZ1945) 8860 ± 120 years B.P. given by Nairn (1980). This latter date is significantly older than our dates, however, hence the specific age of the Rotoma Ash eruption is uncertain.

Fig. 7 (continued).

C Particle-size distribution of subgyttja alluvial samples S-1 to S-3. Grading curves of various lithofacies of Hinuera Formation sediments are shown for comparison (mainly after Hume et al. 1975; the majority of the unlabelled curves represent lithofacies A1 or C1).



D Ternary diagrams comparing relative abundances of ferromagnesian minerals (summed to 100%, see also Table 3) of upper unit tephric materials (U-1 to U-8) with those of some late Pleistocene tephras that are their possible correlatives. On this basis, the bulk of the upper unit is probably derived from Hauparu Tephra, aged c. 37 000 years; Tahuna Tephra, aged c. 38 000 years; and Rotoehu Ash, aged c. 40 000–50 000 years (McGlone et al. 1984b; see C-14 dates in Fig. 8). In diagram i, amphibole consists of calcic hornblende plus cummingtonite. Rotoehu Ash is characterised by a high cummingtonite content (diagram ii—Lowe 1981; Hogg & McCraw 1983). Data sources for the mineralogies of the late Pleistocene tephras are given in note (d) of Table 3.



lar & Birrell 1973). The average age of 12 400 years we obtained for Waiohau Ash in Lake Maratoto is significantly older than this. This difference in age may result from an “error” in the Lake Maratoto dates due to contamination by redeposited organic material (cf. Björck & Håkansson 1982). Alternatively, the previous ages on the Waiohau Ash, all determined on charcoal which is very susceptible to contamination (Hogg 1982), may be underestimates. We prefer the older age (12 400 years), but the age discrepancy nevertheless signifies that the chronology in this zone of the cores is less certain than in the others.

LAKE SEDIMENT CHARACTERISTICS AND SEDIMENTATION RATES

The characteristics of the four types of lake sediment described are summarised in Table 4. Since the bulk of the sediment probably originates in the catchment, as in other small lakes (e.g., Mackereth 1966), we have made broad inferences about conditions in the catchment using this classification. In addition, we use sedimentation rates to indicate rates of erosion in the catchment.

Sediment type 1 (T1), largely inorganic, suggests that catchment soils had a low organic content with

Table 3 Mineralogical composition of the sand fractions of subpeat and subgyttja samples at Lake Maratoto*. Compositions of some widespread late Pleistocene tephras (note d below) and Hinuera Formation sediments are included for comparison with upper unit (U-1 to U-8) and Hinuera (S-1) samples, respectively. Some of the ferromagnesian mineralogical data is plotted in Fig. 7D.

Samples	Heavy minerals ^a					Accessory minerals (as % of heavy minerals)		Light minerals ^b (relative abundances)
	Ferromagnesian silicate minerals (summed to 100%)					Zir	Mag	
	Hyp	Aug	Hbe	Cgt	Bio			
Hinuera^c								
S-1	65	17	17	0	1	tr	12	g ≫ f > q
Hinuera Formation ¹	75	8	14	0	3	0	38	g ≫ f ≫ q ≫ l
Upper unit (cm)†								
U-5 (5-12)	45	30	20	5	0	2	5	g ≫ f ≫ q
U-3 (10-15)	60	15	21	2	2	1	18	g ≫ f ≫ q
U-7‡ (30-33)	59	25	16	0	0	2	6	g ≫ f > q
U-8‡ (40-42)	31	3	65	1	0	3	17	g ≫ f > q
U-6 (45-50)	51	22	18	9	0	2	9	g ≫ f ≫ q
U-4 (50-55)	31	20	33	16	0	2	7	g ≫ f ≫ q
U-1 (60-65)	40	4	34	22	0	1	18	g ≫ f ≫ q
U-2 (100-105)	24	11	30	35	0	tr	14	g ≫ f ≫ q
Tephra^d								
Okareka Ash ^{2, 3}	16-23	1-9	20-61	0-1	19-49	5	30	g ≫ f ≫ q
Kawakawa Tephra ^{3, 4}	41-62	2-20	23-53	0	0-2	1-2	33-38	g ≫ f > q
Hauparu Tephra ^{5, 6}	38-83	15-38	0-32	0-1	0	nd	nd	nd
Tahuna Tephra ^{3, 4, 7}	32-60	tr-12	26-65	0-2	0-2	1-3	47-54	g ≫ f ≫ q
Rotoehu Ash ^{4, 5, 7}	7-16	0-2	1-44	47-91	0-2	1-3	28-51	g ≫ f > q
"Composite" ^{e, 4}	30-39	11-21	24-29	16-31	0-2	1-2	32-67	g ≫ f > q

a = S.G. > 2.9 g/cm³: Hyp = hypersthene; Aug = augite; Hbe = calcic hornblende; Cgt = cummingtonite; Bio = biotite; Zr = zircon; Mag = predominantly titanomagnetite.

b = S. G. < 2.9 g/cm³: g = glass (and rare pumice); f = feldspars (mainly plagioclase); q = quartz; l = lithics.

c = Hinuera Formation sediments are volcanogenic with diverse mineralogy. Data source: 1 = Hume et al. (1975).

d = Widespread rhyolitic tephras of c. 17 000 - c. 50 000 years age range that are predicted to be the most likely constituents of the Upper unit. Values show the characteristic range of mineral abundances in each tephra from various localities in the North Island. Data sources and locations are: 2 = D. J. Lowe, unpublished data (Lake Rotomanuka, Fig. 1); 3 = Howorth et al. (1980) (Poukawa; Gavin Road; Whangamata Road; Okataina area); 4 = Lowe (1981) (Waikato); 5 = Hogg & McCraw (1983) (Coromandel); 6 = McGlone et al. (1984b) (Bay of Plenty-Gisborne); 7 = Vucetich & Howorth (1976b) (Taupo). Data in the "Accessory minerals" and "Light minerals" columns are derived wholly from references 2 and 4 above.

e = "Composite" refers to a composite of pedogenically mixed late Pleistocene and Holocene tephras that occur as c. 50-150 cm thick cover bed deposit on the low hills in the Hamilton City-Lake Maratoto area (Lowe 1981).

*Sands (2-4φ) were fractionated by sieve and heavy liquid separation methods and analysed by standard petrological microscope (point-count) and X-ray diffraction procedures.

†Depth of sample below base of peat or paleosurface.

‡U-7 and U-8 occur as discrete, apparently pure tephra layers and probably represent the Hauparu Tephra and Tahuna Tephra, respectively (see text).

tr = trace amount (< 1%); nd = not determined.

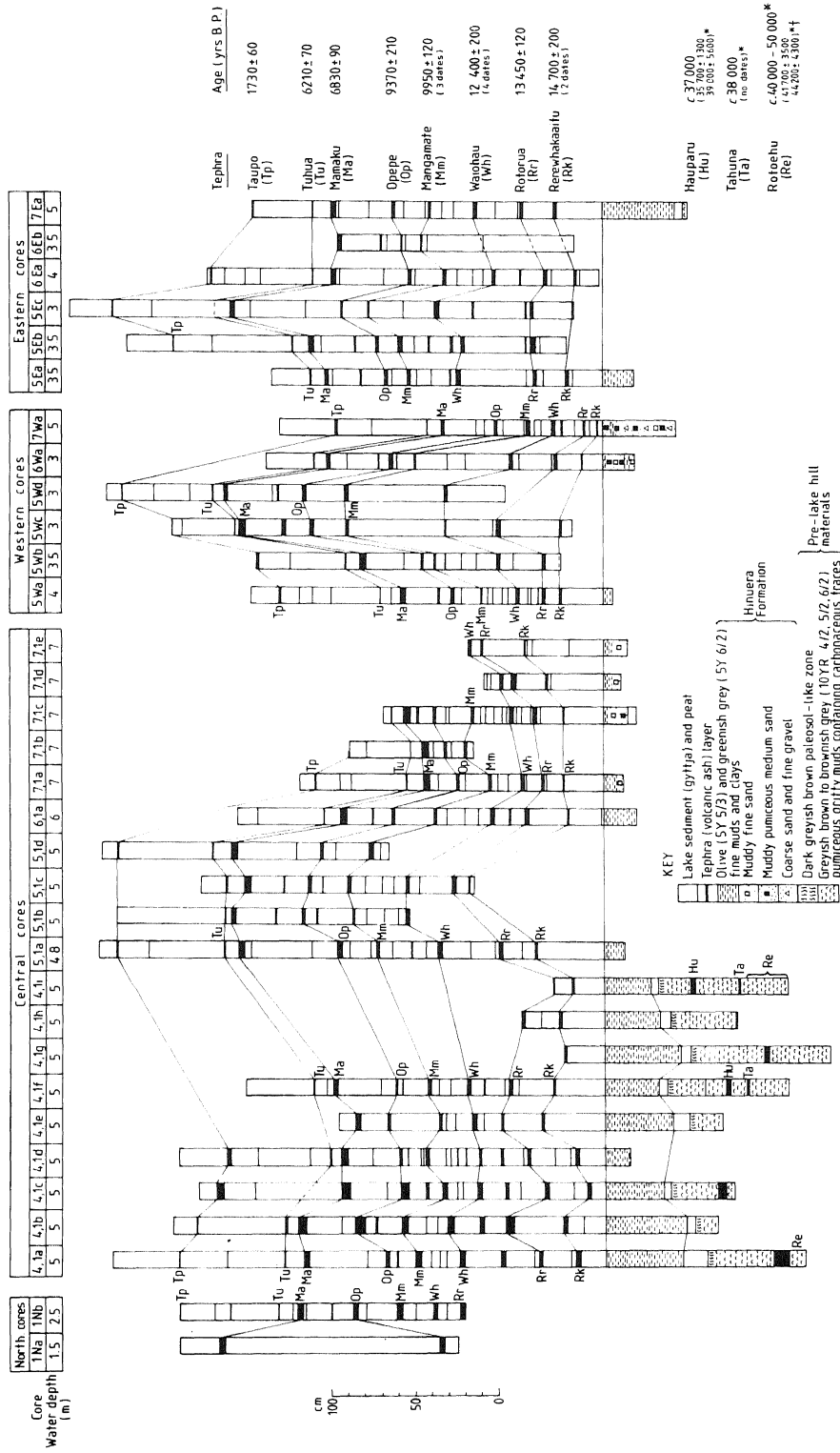


Fig. 8 Stratigraphy, lithology, and chronology of the lake sediment cores. Coring locations are shown in Fig. 3. Tephra identifications are based on Lowe et al. (1980) and work currently in progress (see text and Tables 1-3). The majority of the tephra are derived from the Okataina and Taupo Volcanic Centres; others originate from Mayor Island, Tongariro, and probably Mount Egmont sources. Ages of the distinctive tephra used throughout the lake as time planes (right-hand column) are from Fig. 9. Sediment descriptions generally follow Folk's (1968) nomenclature. The colours are based on Munsell notation.
 *Ages from McGlone et al. (1984b, table 1, p. 333). †Ages from Pullar & Heine (1971) and McGlone et al. (1984b).

Tephra	Waikato Radiocarbon Dating Laboratory No	Age (years B.P.) ¹		Sample ²
		T _{1/2} OLD	T _{1/2} NEW	
Taupo Pumice	Wk 215*	1730 ± 60	1750 ± 60	g
Tuhua Tephra	Wk 214*	6210 ± 70	6420 ± 70	g
Mamaku Ash	Wk 227	6830 ± 90	7050 ± 100	g
Rotoma Ash	Wk 523	8350 ± 100	8600 ± 100	g
	Wk 522	8370 ± 90	8620 ± 100	g
Opepe Tephra	Wk 230	9370 ± 210	9680 ± 220	g
Mangamate Tephra	Wk 231	9700 ± 140	10000 ± 140	g
	Wk 232	10000 ± 120	10400 ± 120	g
	Wk 213*	10120 ± 100	10440 ± 100	g
	Wk 553†	10600 ± 90	10950 ± 90	p
Waiohau Ash	Wk 516	12300 ± 190	12700 ± 190	g
	Wk 233	12200 ± 230	12600 ± 240	g
	Wk 234	12500 ± 190	12900 ± 200	g
	Wk 515	12450 ± 200	12810 ± 200	g
Rotorua Ash	Wk 511	13450 ± 120	13850 ± 120	g
Rerewhakaaitu Ash	Wk 237*	14700 ± 220	15200 ± 230	g
	Wk 238*	14700 ± 180	15200 ± 190	g
	Wk 534†	15200 ± 130	15650 ± 140	p
	Wk 239	16300 ± 250	16800 ± 270	g
	Wk 510	15850 ± 130	16300 ± 130	g
Hinuera Formation (overbank mud deposits)				
	Wk 509	16200 ± 360	16650 ± 370	g
		-340	-350	
Proto-Lake Maratoto gyttja	Wk 240	16900 ± 470	17500 ± 490	g
Palaeosol	Wk 358	17050 ± 200	17620 ± 210	g
Pre-lake hill materials				

Fig. 9 Summary of radiocarbon dates on gyttja and peat deposits in the Lake Maratoto area.

¹All ages discussed in the text are old half-life dates.

²g = gyttja; p = peat.

*Dates published by Lowe et al. (1980).

†Samples of basal peat in cores GC1 and RJ1 (Fig. 5) — stratigraphic positions inferred from ages. Peat sample Wk114 (10250 ± 90 years B.P.) was collected from the base of the Rukuhia bog at 8.3 m depth about 6 km northwest of Lake Maratoto (near grid ref. S15/076694); sample Wk115 (10750 ± 90 years B.P.; McGlone et al. 1978) was collected at 9 m depth about 3 km north of Lake Maratoto (near S15/119691) (A. G. Hogg pers. comm. 1983). Grid references are based on the national 1000 m grid of the topographical map series (NZMS 260).

Table 4 General descriptions of four classes of lake sediment in Lake Maratoto.

Type	Sediment description	Munsell colour notation (range)	Organic matter %*	Occurrence in present-day Lake Maratoto†
T4	Black fibrous soft peaty sediment containing plant fragments > 2 mm	10YR 2/1	54.2	Around lake margins to depths of 1 m
T3	Black to very dark brown fine soft dy-gyttja. Particles < 1 mm	10YR 2/1 10YR 2/2	42.7	Water depths > 1 m
T2	Very dark grey to very dark greyish-brown firm fine gyttja. Particles < 1 mm	10YR 3/1 10YR 3/2 2.5Y 3/2	18.9	Not found in surficial sediments
T1	Olive to very dark grey, firm slightly sticky fine gyttja. Particles < 1 mm	5Y 3/1 5Y 3/2 5Y 4/3	9.1	Not found in surficial sediments

*Loss on ignition determined on at least two samples of dried sediment by combusting at 550°C for 30 min.

†From Boubée (1983).

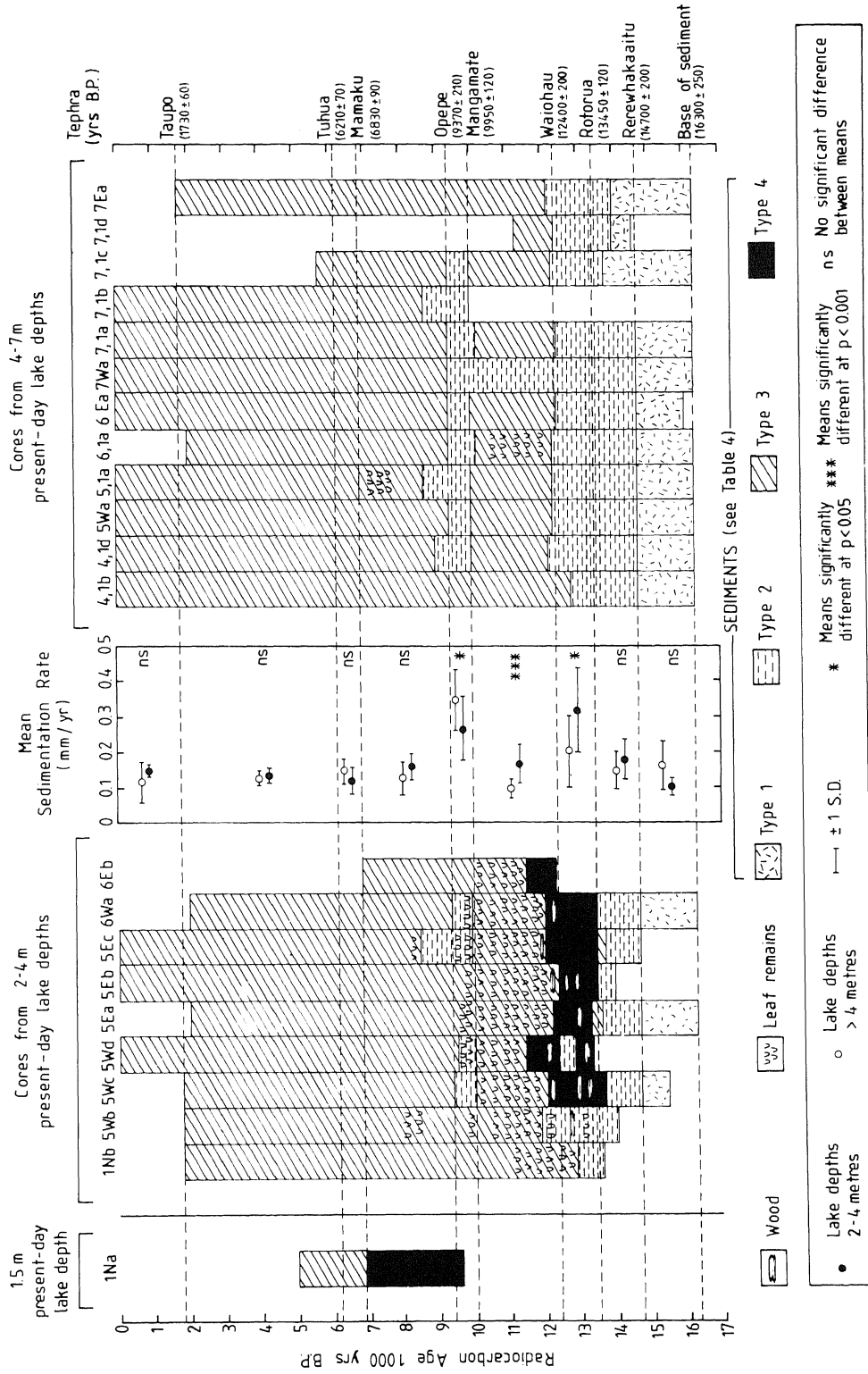


Fig. 10 Changes in lake sediment type over time in cores grouped into shallow-water and deep-water cores. Mean sedimentation rates for each time period (denoted by horizontal dashed lines) in both deep and shallow water cores, and the results of a *t*-test of the significance of their difference, are also given. Coring locations are shown in Fig. 3.

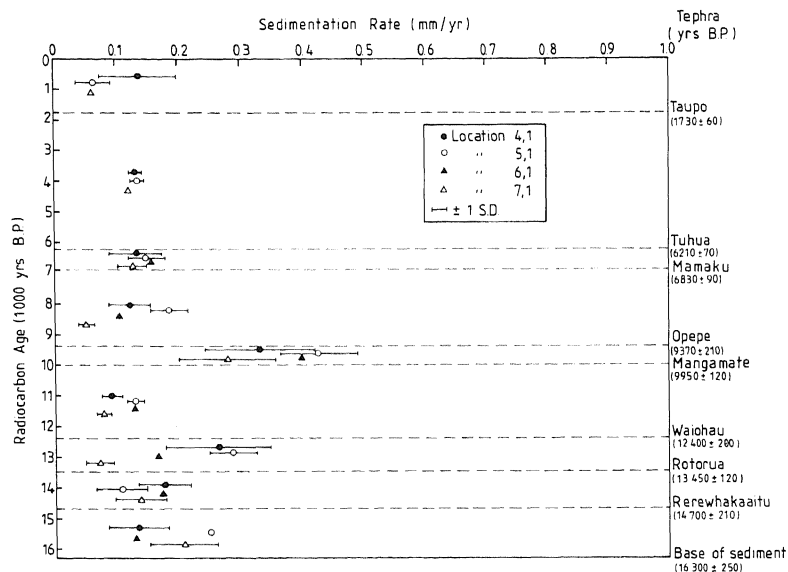


Fig. 11 Sedimentation rates in cores taken from central locations (along transect 1-1' in Fig. 3) and averaged for each designated time period (denoted by horizontal dashed lines).

little vegetational cover. The greenish tinge of this sediment is due largely to secondary chlorophyll degradation products, possibly produced within the lake itself. The lack of brown staining implies that the lake water was clear. The browner T2, with higher organic content, suggests more vegetation in the catchment and soils with greater organic content. Marginal vegetation may have contributed also to its darker colour. The very dark peaty T3 consists of decomposing remains of aquatic plants and animals, faecal pellets of aquatic animals, and fine plant remains from surrounding terrestrial vegetation (Boubée 1983), and is stained with humic material extractable with 10% KOH. Such sediment, often described as dy-gyttja (e.g., Hansen in Berg & Petersen 1956), shows dystrophic conditions in the lake and considerable peat development around it. Leafy fragments occur in T3 sediment within and around beds of the sedge *Eleocharis sphacelata*. T4 sediment is fibrous and woody and is similar to peat from the Rukuhia bog. It is found around the margins of the present-day lake (Table 4).

Changes in sediment type and sedimentation rates were examined in two groups of the lake sediment cores—those taken from modern lake depths shallower than 4 m (shallow-water cores) and those taken from depths deeper than 4 m (deep-water cores) (Fig. 10).

The temporal sequence is similar in most of the deep-water cores (Fig. 10, right panel). Sediment T1 occurs from c. 16 300 to 14 700 years ago, T2 from 14 700 to c. 12 400 years ago, and T3 thereafter, except for a brief period of T2 deposition from

10 000 to c. 9000 years ago. No T4 or wood was found in the deep-water cores, and leaf remains are rare. Most of the shallow-water cores (Fig. 10, left panel) differ from the deep-water cores in having a band of woody T4 from c. 13 500 to c. 12 000 years ago, leafy T3 from c. 12 000 to 10 000 years ago, and a less-obvious zone of T2 from c. 10 000 to 9000 years ago.

For most of the lake's history (c. 16 300–13 500 years ago, c. 12 400–10 000 years ago, and c. 9000 years ago to present) (Fig. 10), mean sedimentation rates were slow (0.10–0.20 mm/year). For two brief periods, from c. 13 500 to 12 400 years ago, and from c. 10 000 to 9000 years ago, the sedimentation rate was faster (0.20–0.35 mm/year).

There was no significant difference in sedimentation rate between shallow and deep water cores early (c. 16 300–13 500 years ago) and late (from c. 9000 years ago to present) in the lake's history. However, from c. 13 500 to 10 000 years ago, sedimentation rates in shallow water were significantly faster than in deep water. During this period, sediment types T4 and leafy T3 were deposited in shallow water. In contrast, from c. 10 000 to 9000 years ago, sedimentation rate was significantly faster in deep water, coinciding with T2 deposition. This was the only period of sediment focussing (i.e., greater accumulation of sediment in the deepest part of a lake basin; Davis & Ford 1982) in the lake's history.

In central locations (along transect 1-1'; Fig. 3), between c. 16 300 and 12 400 years ago, sedimentation rates declined in the south of the lake (location 7,1) but increased in the northern (4,1) and middle (5,1) locations (Fig. 11). Thereafter,

Table 5 Total lake sediment thickness in central locations.*

Location	No. of cores used in calculation	Sediment thickness (cm)
4,1	4	259
5,1	1	310
6,1	1	251
7,1	2	201

*Data also plotted in transect 1-1', Fig. 4.

from c. 13 500 to 7000 years ago, sedimentation rate was consistently slowest in the south and fastest in the middle (narrow) area of the lake. The faster sedimentation rates in location 5,1 from c. 13 500 to 7000 years ago account for the greater total sediment thickness there (Table 5). From c. 7000 to 2000 years ago, sedimentation rate was similar in all central locations. Sedimentation rates were faster in the northern basin (4,1) from c. 2000 years ago to the present.

In the central locations (transect 1-1'), sedimentation rates were inversely proportional to the distance from the shoreline (e.g., station 7,1 is 150 m, and station 5,1 is 50 m, from the shore), suggesting that input of littoral and terrestrial material is the major factor determining the sedimentation rates in Lake Maratoto.

DEVELOPMENTAL HISTORY

Origin of the lake basin

Beneath the lake is a shallow, elongated, northeast-southwest-orientated depression. This is an embayment in the Pleistocene hills which is dammed to the southwest by Hinuera sands and gravels and flooded by Hinuera muds and clays (Fig. 12). The southwest margin of the paleosurface depression, made up of these Hinuera sands and gravels, is lower lying than the low ridges and Pleistocene hills around its other sides. The lake is thus held at its present level mainly by the 8 m depth of peat overlying the sands and gravels to the southwest.

The Hinuera sediments blocking the embayment were laid down in two main episodes (Fig. 13), the first of which occurred c. 17 000 years ago forming a proto-Lake Maratoto in which the thin layer of gyttja lying beneath the Hinuera muds was deposited. The proto-Lake Maratoto gyttja lies directly on the Pleistocene hill derived materials in the valley floor with no intervening layer of Hinuera muds, at least in the northern part of the lake basin. This suggests either that there was no extensive flooding

by mud-laden river water, possibly because the major course of the Waikato River moved some distance away from the mouth of the valley after deposition of the dam materials, or that the basin was too shallow to hold enough water to produce an appreciable thickness of mud. Whichever, this proto-Lake Maratoto sediment was laid down in what may have been a swampy hollow with only shallow water. The duration of the proto-lake was between 150 and 800 years (Fig. 9).

The second episode of Hinuera deposition, that produced the initial modern lake basin, was more extensive and rapid. There must have been a considerable depth of floodwater ponded in the valley to act as a buffer to the river current to produce the sorted nature of Hinuera deposits in the embayment (Fig. 13). The alternating sand and mud layers found in the base of the cores from the southwest of the lake and in GC1 (Fig. 5, 8) suggest that the ponded mud-laden water was renewed in a series of floods. This is consistent with what is inferred about Hinuera Formation deposition by Hume et al. (1975) who deduced that the river formed an extensive braided channel system with high flow-rates and subject to periodic flooding and channel movements. Hume et al. (1975) identified several lithofacies related to flow regimes, and their lithofacies C2, formed by plane bed movements on the surface of longitudinal bars at higher discharges, is very similar to the gravelly sands in core 7Wa (Fig. 7C, 8). The presence of such deposits at this site shows that, at least during periods of high flow, the main channel system of the river flowed near the mouth of the valley. The river may have flowed in a north-south direction broadly along the course shown in Fig. 1 from the site of the present-day Hamilton Airport, past the lake, and then west into the Waipa River near Te Rore. Lakes Cameron, Ruatuna, Ngaroto, and Mangakaware, which lie adjacent to this paleochannel, are thus likely to have been formed at the same time, and in the same way, as Lake Maratoto.

Development of the lake basin and catchment

Initially, the lake was probably no larger than it is today because fine gyttja does not occur in the RJ1 core at the southwestern edge of the lake nor in GC3 only 10 m from the northern lake shore. At c. 16 300 years ago, the shoreline probably lay between the 7 and 8 m paleobasin contours (Fig. 12). The RJ1 core site lies on the 7 m contour and was clearly either above water or close enough to the shoreline for wave action to remove any gyttja to deeper water. The 8 m contour, however, seems to have been under water from the start of the lake's development, and cores from sites 5W, 6W, and 7W, that are on or close to this contour line, have

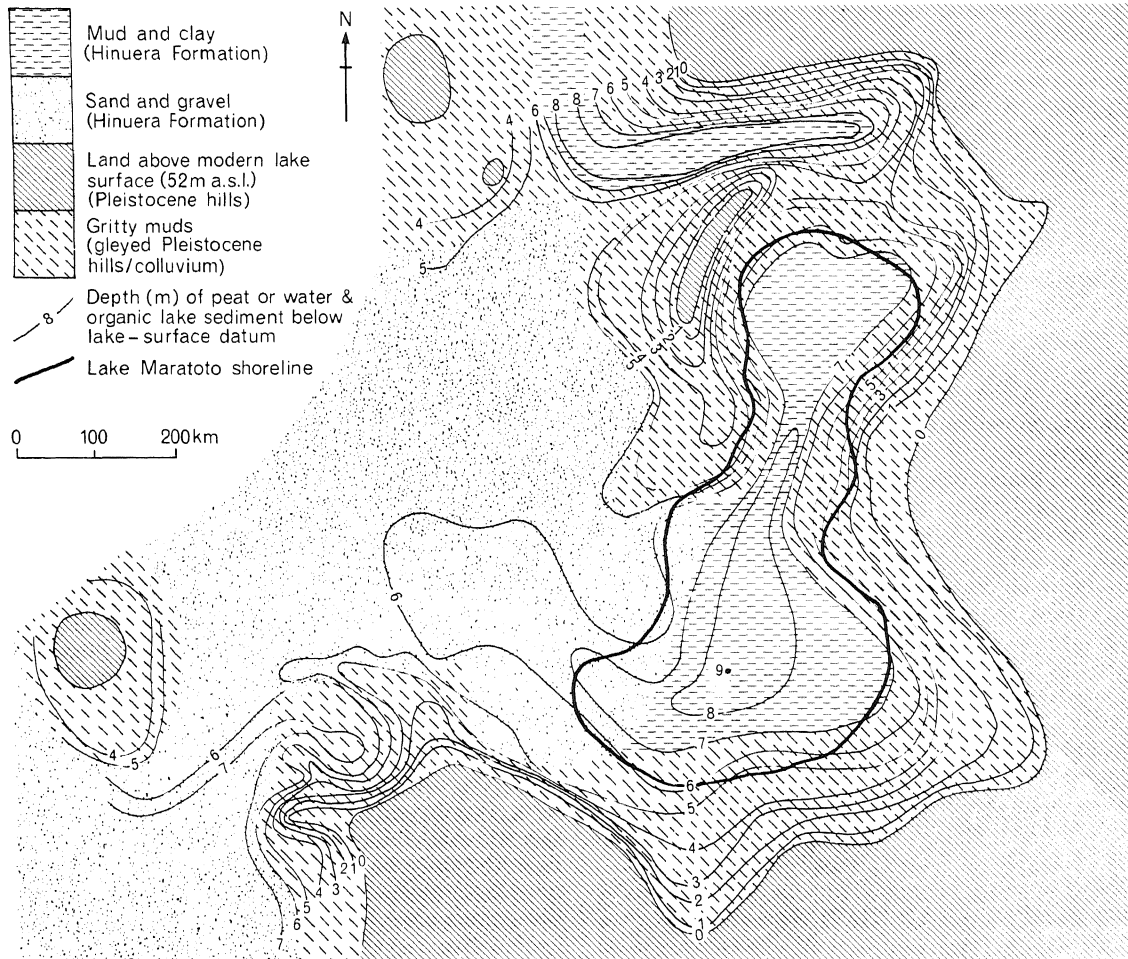


Fig. 12 Subsurface materials and topography of the Lake Maratoto area, derived from the transect profiles in Fig. 4. The 0 m contour is the lake-surface datum (52 m altitude). The map shows the northeast-southwest-orientated depression in which the modern lake (heavy line) lies. A separate, narrow, east-west-orientated paleovalley occurs to the north of Lake Maratoto. See also Fig. 13.

a considerable thickness of gyttja between the Hinuera overbank muds and the Rerewhakaaitu tephra. The lake would thus have been about 2 m deep in its early stages.

The subsequent development of the lake has been largely governed by the massive growth of peat around its margins and in the adjacent Rukuhia bog, as well as by the accumulation of gyttja. Peat growth has modified the basin configuration (area and depth) and water chemistry.

There was little or no peat development during the first 1000 years or so of the lake's history. The type of sediment deposited shows that lake water was clear and that, in the catchment, soils were low

in organic matter, with probably little vegetational cover. From pollen analyses of peat lenses, McGlone et al. (1978) and McGlone et al. (1984a) concluded that there was sparse vegetation in the Hamilton region at this time.

Peat began to accumulate around the lake about 15 000 years ago, as shown by the date (Wk534) of $15\ 200 \pm 130$ years ago at the base of RJ1. The appearance of darker coloured T2 in the lake may have resulted from such peat development although other factors, such as increasing vegetational cover in the catchment, may have been important. Elsewhere in the central North Island, 14 700 years B.P. marked the beginning of major podocarp forest expansion (e.g., McGlone & Topping 1977; Flem-

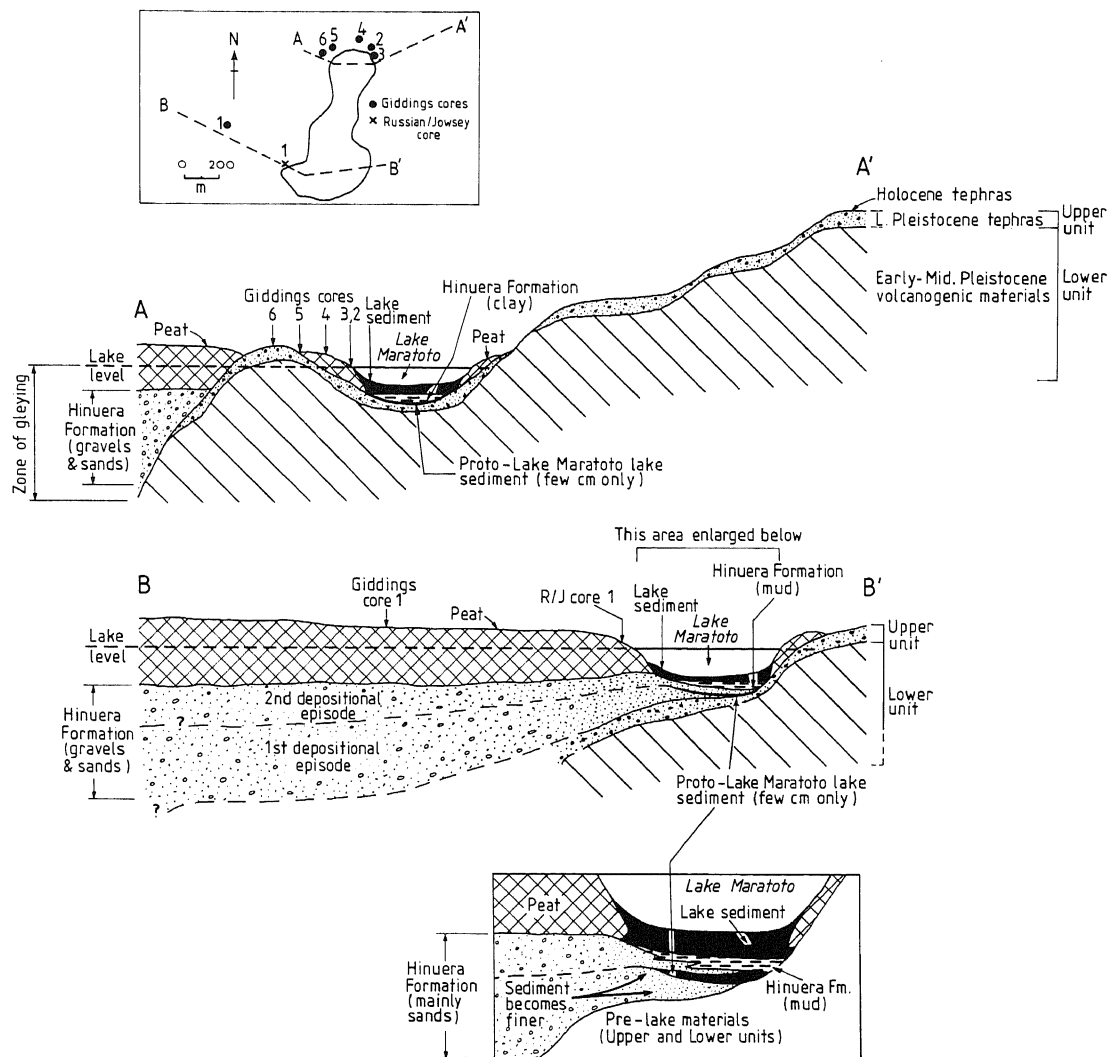


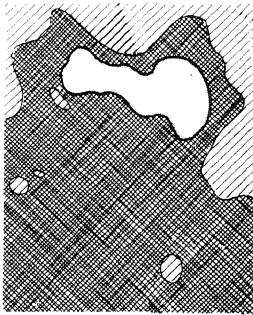
Fig. 13 Schematic cross sections summarising the stratigraphic units and their relationship to one another in the Lake Maratoto area, showing especially the differences between the northern and southern parts of the lake basin. There is a time gap of a few hundred years between the Hinuera depositional episodes shown in B-B', but note that both occurred within the Hinuera-2 sedimentation phase of McGlone et al. (1978).

ing 1979) and an increase in rates of soil formation (e.g., Vucetich & Pullar 1969; Birrell & Pullar 1973). This early peat development must have been fairly localised because the change to T3, marking the onset of dystrophy, did not occur until c. 12 400 years ago, and peat did not appear at the GC1 site, only 400 m from the lake, until (Wk553) 10 600 ± 90 years ago. Thus it seems peat first developed near the lake and then spread outwards.

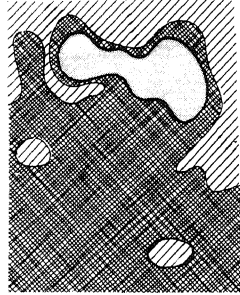
Dates from peat at the base of the main body of the Rukuhia bog (10 750 ± 90 years B.P. (Wk115)

McGlone et al. 1978; 10 250 ± 90 years B.P. (Wk114) unpublished) (Fig. 9) are similar to that for GC1, showing that most bog development occurred after c. 11 000 years ago. Peat bogs began developing at other sites in the Waikato region (e.g., Hauraki and Moanatuatua bogs—Schofield 1965; McGlone et al. 1978; Hogg & McCraw 1983) and elsewhere in the North Island (McGlone & Topping 1977; Lowe & Hogg in press) at about this time also, which suggests that climatic change resulting in an increase in net precipitation, and

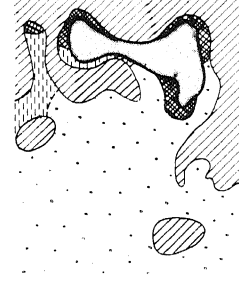
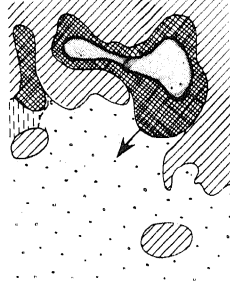
Present day The lake basin is formed in the surrounding peat, perched above and divorced from the initial lake basin in the valley floor. Area and depth of lake at maximum. Other lakes similar to present-day Lake Maratoto, and thus possibly of a similar ontogenetic stage, include Cameron, Pataka, Posa, and D.



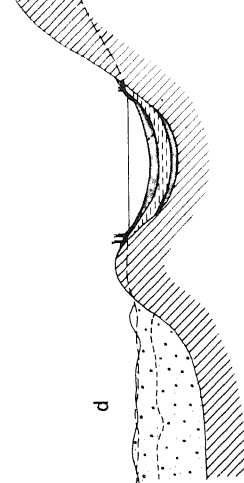
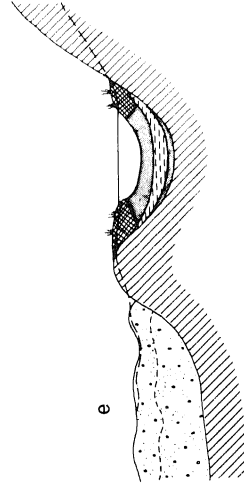
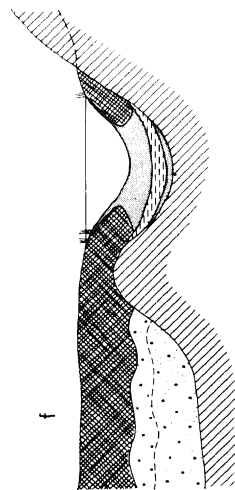
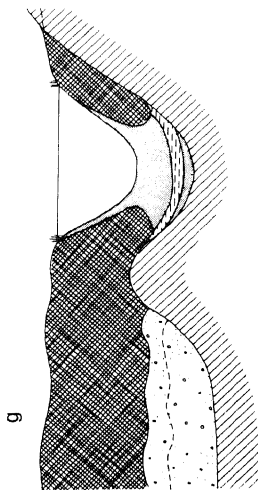
10 000 years ago to present Rukuhia peat bog expands, most rapidly after c. 7000 years ago. Water deepens as rate of peat growth is much greater than gyttja sedimentation rate in the lake. Water depth perhaps 3.5 m at 7000 years ago, 6.5 m at 2000 years ago. Lake area gradually expands but is never larger than at present. Lake dystrophic. A sequence of modern lakes possibly illustrating the development in the first part of this period is Lakes Mangahia, Rotoroa, Ruatuna, and Serpentine.



14 000 to 10 000 years ago Marginal peat and swamp vegetation encroaches into lake and reduces its surface area by half at c. 13 000 years ago. From 13 000 to 10 000 years ago, lake area expands again and water deepens. Main body of Rukuhia bog begins growth at c. 11 000 years ago, and the peat growing westward (arrow) from the lake contributes to this development. Dark brown-black gyttja of high organic content because of peat growth and extensive catchment vegetation. Lake becomes dystrophic. Water 2.5 m deep at 10 600 years ago. Modern analogues include Lakes Rotomanuka, Rotokauri, Mangakaware, and Ngaroto.



16 300 to 14 000 years ago Initial lake development. Gytija olive-grey, low in organic matter. Gytija darkens later in the period because of development of marginal peat (at 15 200 years ago) and possibly catchment vegetation. Water clear, still c. 2 m deep. Modern analogues are Lakes Waahi and Hakanoa.



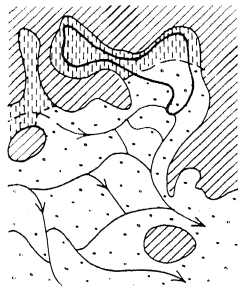
g

f

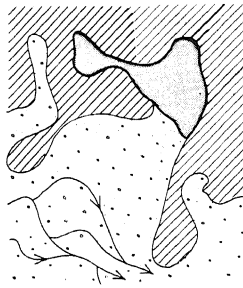
e

d

16 300 years ago Second phase of Hinuera deposition in the area. Coarse sediment deposited in valley mouth, fining to muds and clays at the end of the valley. Lake Maratoto forms, c. 2 m deep, with its shoreline approximating the 7 m contour in Fig. 12. Lake water clear. No peat, and sparse vegetation in catchment.



17 000 years ago First phase of Hinuera-2 deposition in the area. Proto-Lake Maratoto forms by damming of the valley by alluvium. Basin swampy or with only very shallow water.



Before c. 17 000 years ago Valley in Pleistocene hills draining to the southwest and west. Clear area represents land below c. 40 m contour.

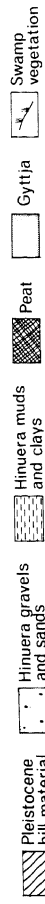
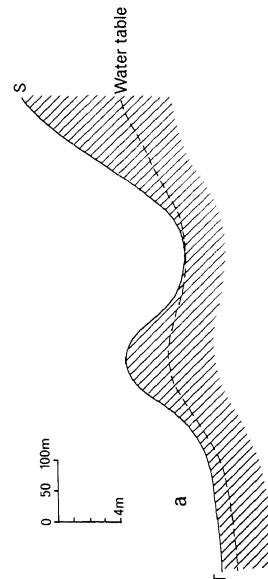
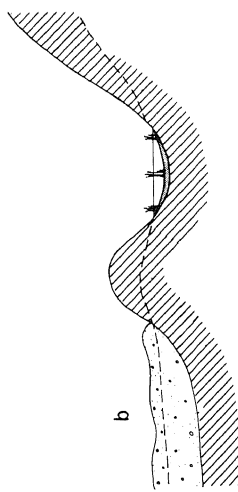
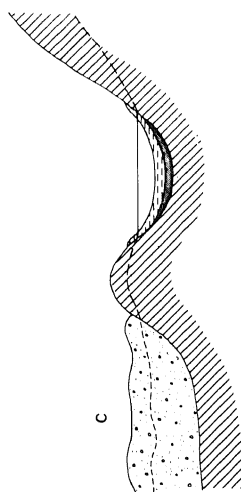
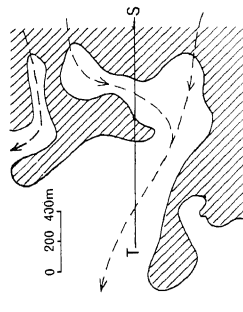


Fig. 14 (above and facing page) Summary of the developmental history of Lake Maratoto (bold outline). Cross sections have a vertical exaggeration of $\times 25$. Possible modern analogues (see Fig. 1) of the major development stages are given also.

not local-changes in drainage patterns, initiated the development of the bog.

The dystrophic conditions induced in the lake by the development of the Rukuhia bog have continued to the present, except for the brief period of T2 deposition from c. 10 000 to 9000 years ago. This was probably a time of increased input of material derived from erosion of surrounding soils because T2 has a higher inorganic content than T3. Possible explanations include sustained high rainfall, or disruption of catchment vegetation by events such as fire, drought, or increased storminess. Sediment focussing also occurred during this period, with greater transport of littoral material to the centre of the lake by (presumably) increased wave erosion at the shoreline. Such focussing is consistent with wetter or windier weather at this time.

The vertical distance between the bases of cores RJ1 and GC1 is 1.1 m and their respective ages are 15 200 and 10 600 years, so 1.1 m of peat accumulated in this time interval (4600 years), a net peat accumulation rate of 0.03 cm/year. This peat growth would not have greatly affected the lake depth because in this period about 65 cm of lake sediment was deposited. The net change of lake depth was thus 45 cm and the rate of increase in water depth was 0.01 cm/year. The lake would thus have been about 2.5 m deep at 10 600 years ago. The main body of the Rukuhia bog developed after c. 10 600 years ago, and with a much greater net peat accumulation rate (e.g., at GC1, 8 m of peat has accumulated since then, giving a net peat accumulation rate of 0.08 cm/year, treble the rate between 15 200 and 10 600 years ago). Similar rates of 0.10, 0.06, and 0.08 cm/year (average 0.08 cm/year) were estimated from peat depths between Mamaku tephra and Taupo tephra in cores RJ1, GC2, and GC3, respectively (Fig. 5).

This rapid peat growth around Lake Maratoto resulted in rapid deepening of the water. From 10 600 years ago to the present, the rate of peat growth was much greater than the rate of accumulation of lake sediment, and lake depth increased by 4.6 m, a change of 0.04 cm/year, four times the rate before 10 600 years ago. Assuming that the positions of the Mamaku and Taupo tephra in the peat cores mark the approximate level of the lake surface when they were deposited, and that the peat has not been compressed, we estimate that lake depth was 3.5 m c. 7000 years ago and 6.4 m c. 1800 years ago. Thus, between 10 600 and 7000 years ago, the rate of change of lake water depth was 0.03 cm/year; between 7000 and 1800 years ago, 0.06 cm/year; and from 1800 years ago to the present, 0.04 cm/year. Thus, lake depth has increased markedly in the last 11 000 years, but particularly since 7000 years ago.

Variations in the spatial pattern of the deposition of lake sediment have resulted in minor modifications to the bathymetry. Early in the lake's history, lake depth gradually increased from north to south, but because sedimentation rates were fastest in the region of core location 5,1 (because of nearness to the shoreline), there is now a shallower zone in the narrow waist of the lake (Fig. 2).

Although the area of the lake in its early stages was probably similar to that of today, the band of woody T4 sediment in the shallow-water cores between c. 13 500 and 12 400 years ago (Fig. 10) shows that during this period the lake margin moved inward to lie near the position of these coring sites, between the 3 m and 4 m water depth contours. The change to leafy T3 sediment between c. 12 400 to 10 000 years ago at these sites shows that the shoreline moved outward again, but was still close to the 3 m and 4 m depth contours. The faster rates of sedimentation in shallow-water cores from 13 500 to 10 000 years ago reflect this proximity of the shoreline to the coring sites and also suggest little movement of littoral material into deeper water. The disappearance of leafy T3 sediment from the shallow-water cores after about 10 000 years ago shows that lake area continued to expand. The shoreline reached the present 1.5 m water depth contour at about 7000 years ago, as shown by the abrupt transition from T4 to T3 sediment at this time in core 1Na (Fig. 10). Thereafter, expansion continued to the present day. This shoreline expansion in the last 10 000 years occurred together with the increase in water depth.

Throughout its history, the lake has never been larger than it is now, while at its minimum at c. 13 000 years ago, the area of open water was only about one-half that of today (7.6 ha using the 3.5 m depth contour).

Most lakes occupying basins in which peat development is occurring are gradually reduced in area and depth by centripetal peat growth that eventually develops into zones of "quaking bog", made of floating mats of encroaching peat vegetation and often supporting large trees (Moss 1980). The final result of this process is extinction of the lake. The complete process from lake origin to extinction can take less than about 12 000 years in the Northern Hemisphere (e.g., Pigott & Pigott 1963; Walker 1970). The only lake we know of which has a similar developmental history to Lake Maratoto is Myrtle Lake, in the Agassiz peatland area of Minnesota (Heinselman 1970). This lake originated as an embayment blocked by alluvium c. 10 000 years ago and, like Lake Maratoto, has maintained its area and increased its depth despite massive peat growth in the catchment during the last 3000–5000 years. Heinselman (1970) suggested

that because of Myrtle Lake's location adjacent to higher areas of mineral soil, it would have continually received minerotrophic water that has enhanced microbial breakdown of the encroaching peat. This explanation may apply to Lake Maratoto as well because there is only a narrow zone of peat between the lake water and the Pleistocene hills to the east (Fig. 2, 4). Also, these hills rise considerably above the lake's surface which would encourage greater flow rates of minerogenic ground and surface water into the lake during heavy rainfall.

Other mechanisms may also be involved in the expansion of Lake Maratoto's area. Wells & Boyce (1953) and Frey (1954) suggested that erosion of peat margins by wave action may have been a factor in the development of the Carolina Bays (North Carolina). This almost certainly occurs in Lake Maratoto. In the present-day lake, a vertical 50 cm high bank is maintained around the lake margins, particularly at the north and south ends, by wave action produced by the prevailing southwest and northerly winds. Wind-induced currents stir and aerate the lake waters for most of the year. The lake develops thermal stratification and deoxygenated bottom waters for only a few months in the summer (Boubée 1983), hence the lake waters are usually saturated or supersaturated with oxygen which will enhance organic breakdown.

Our interpretation of the development of the lake basin is summarised in Fig. 14, along with possible modern analogues of the major developmental stages.

CLIMATIC INFERENCES

Between c. 17 000 and 15 000 years ago, there seemed to be no peat development near the lake. The first appearance of peat at c. 15 000 years ago may indicate that effective rainfall increased at this time. Subsequently, net peat accumulation rate, regional water tables, and lake level rose continually until c. 2000 years ago. The major part of the Rukuhia peat bog developed after c. 11 000 years ago, but the fastest growth rates, and thus highest net precipitation rates, were apparently not until after c. 7000 years ago. Regional postglacial climatic warming, reaching a maximum at c. 9000 years ago (Hendy & Wilson 1968), may also have contributed to the peat growth.

In summary, there was a sudden increase in net precipitation at c. 15 000 years ago followed by further increases at c. 11 000 years ago continuing to c. 7000 years ago at least, but with a decline at or before c. 2000 years ago. The period from c. 10 000–9000 years ago may have been distinctly wetter or windier, or both. These inferences are consistent

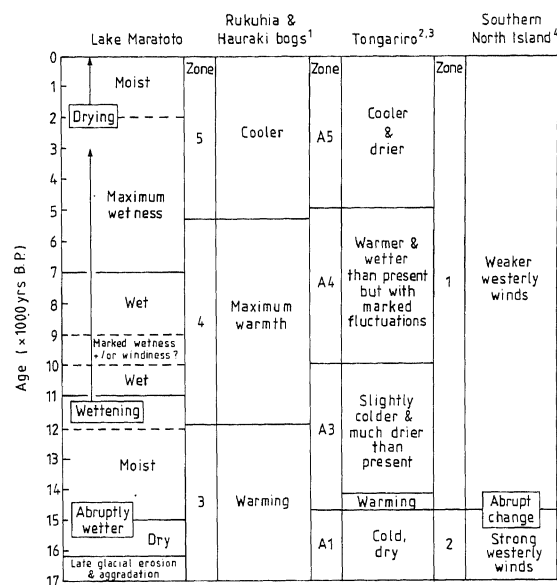


Fig. 15 Inferred changes in climate in the Lake Maratoto area compared with interpretations from some other North Island sites. References are: 1, Harris (1963); 2, McGlone & Topping (1977); 3, McGlone & Topping (1983); 4, Stewart & Neall (1984).

with late-glacial and postglacial climatic interpretations from other studies in the North Island of New Zealand (Fig. 15) (McGlone 1983; McGlone et al. 1984a) and elsewhere in the Southern Hemisphere (e.g., Burrows 1979; Street & Grove 1979; Heusser & Streeter 1980; Colhoun et al. 1982).

ACKNOWLEDGMENTS

We acknowledge valuable help in the field by Drs J. A. T. Boubée and M. A. Chapman, Mr L. J. Gaylor (University of Waikato), and Mrs M. Lowe and Miss T. Lane. We are grateful to Dr A. G. Hogg (University of Waikato Radiocarbon Dating Laboratory) for rapidly processing C-14 dates and for releasing a previously unpublished date (Wk114, submitted by Dr A. T. Wilson and Mr K. Thompson) on the Rukuhia bog. Dr P. C. Froggatt and Messrs G. J. Gosson, K. Palmer, and J. Carter (Victoria University of Wellington) are thanked for their help in obtaining the electron microprobe analyses, and Dr R. Howarth (Victoria University of Wellington) for his useful comments on the manuscript. Mr B. Davies is particularly thanked for willingly providing access to Lake Maratoto.

REFERENCES

- Berg, K.; Petersen, I. C. 1956: Studies on the humic, acid Lake Gribso. *Folia Limnologica Scandinavica* 8: 273 p.
- Binford, M. W.; Deevey, E. S.; Crisman, T. L. 1983: Paleolimnology: an historical perspective on lacustrine ecosystems. *Annual reviews of ecology and systematics* 14: 255-286.
- Birks, H. J. B.; Birks, H. H. 1980: Quaternary paleoecology. London, Edward Arnold. 289 p.
- Birrell, K. S.; Pullar, W. A. 1973: Weathering of paleosols in Holocene and late Pleistocene tephra in central North Island, New Zealand. *New Zealand journal of geology and geophysics* 16: 687-702.
- Björck, S.; Håkansson, S. 1982: Radiocarbon dates from Late Weichselian lake sediments in South Sweden as a basis for chronostratigraphic subdivision. *Boreas* 11: 141-150.
- Boubée, J. A. T. 1983: Past and present benthic fauna of Lake Maratoto with special reference to the Chironomidae. Unpublished D.Phil. thesis, University of Waikato Library, Hamilton, New Zealand.
- Brugam, R. B. 1984: Holocene paleolimnology. Pp. 208-221 in: Wright, H. E. jun. ed. Late-Quaternary environments of the United States. Vol. 2. The Holocene. Minneapolis, University of Minnesota Press.
- Burrows, C. J. 1979: A chronology for cool-climate episodes in the Southern Hemisphere 12 000-1000 yr B.P. *Palaeogeography, palaeoclimatology, palaeoecology* 27: 287-347.
- Cole, J. W.; Nairn, I. A. 1975: Catalogue of the active volcanoes and solfatara fields of New Zealand. *International Association of Volcanology and Chemistry of the Earth's interior. Part XXII*. 156 p.
- Colhoun, E. A.; van de Geer, G.; Mook, W. G. 1982: Stratigraphy, pollen analysis, and paleoclimatic interpretation of Pulbeena Swamp, northwestern Tasmania. *Quaternary research* 18: 108-126.
- Davis, M. B.; Ford, M. S. 1982: Sediment focussing in Mirror Lake, New Hampshire. *Limnology and oceanography* 27: 137-150.
- Deevey, E. S. 1955: Paleolimnology of the upper swamp deposit, Pyramid Valley. *Records of the Canterbury Museum (New Zealand)* 6: 291-344.
- Fleming, C. A. 1979: The geological history of New Zealand and its life. Auckland, Auckland University Press. 141 p.
- Folk, R. L. 1968: Petrology of sedimentary rocks. Austin, Texas, Hemphill's (The University of Texas). 170 p.
- Frey, D. G. 1954: Evidence for the recent enlargement of the "Bay" lakes of North Carolina. *Ecology* 35: 78-88.
- ed. 1969: Symposium on paleolimnology. *Mitteilungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie* 17. 448 p.
- Froggatt, P. C. 1983: Toward a comprehensive Upper Quaternary tephra and ignimbrite stratigraphy in New Zealand using electron microprobe analysis of glass shards. *Quaternary research* 19: 188-200.
- Froggatt, P. C.; Gosson, G. J. 1982: Techniques for the preparation of tephra samples for mineral and chemical analysis and radiometric dating. *Geology Department, Victoria University of Wellington publication* 23. 12 p.
- Grange, L. I.; Taylor, N. H.; Sutherland, C. F.; Dixon, J. K.; Hodgson, L.; Seelye, F. T. 1939: Soils and agriculture of part of Waipa County. *New Zealand Department of Scientific and Industrial Research bulletin* 76. 85 p.
- Harris, W. F. 1963: Paleocological evidence from pollen and spores. *New Zealand Ecological Society proceedings* 10: 38-44.
- Heinselman, M. L. 1970: Landscape evolution, peatland types, and the environment in the Lake Agassiz peatlands natural area, Minnesota. *Ecological monographs* 40: 235-261.
- Hendy, C. H.; Wilson, A. T. 1968: Paleoclimatic data from speleothems. *Nature* 219: 48-51.
- Heusser, C. J.; Streeter, S. S. 1980: A temperature and precipitation record of the past 16 000 years in southern Chile. *Science* 210: 1345-1347.
- Hogg, A. G. 1982: Radiocarbon dating at the University of Waikato, New Zealand. *Occasional report* 8. University of Waikato, Department of Earth Sciences. 52 p.
- Hogg, A. G.; McCraw, J. D. 1983: Late Quaternary tephra of Coromandel Peninsula, North Island, New Zealand: a mixed peralkaline and calcalkaline tephra sequence. *New Zealand journal of geology and geophysics* 26: 163-187.
- Howorth, R.; Froggatt, P. C.; Robertson, S. M. 1980: Late Quaternary volcanic ash stratigraphy of the Poukawa area, central Hawke's Bay, New Zealand. *New Zealand journal of geology and geophysics* 23: 487-491.
- Hume, T. M.; Sherwood, A. M.; Nelson, C. S. 1975: Alluvial sedimentology of the Upper Pleistocene Hinuera Formation, Hamilton Basin, New Zealand. *Journal of the Royal Society of New Zealand* 5: 421-462.
- Irwin, J. 1982: Lake Maratoto: Lake Mangakaware bathymetry 1:2000. *New Zealand Oceanographic Institute chart, lake series*.
- Kear, D.; Schofield, J. C. 1978: Geology of the Ngaruahia Subdivision. *New Zealand Geological Survey bulletin* 80. 168 p.
- Kennedy, N. M.; Pullar, W. A.; Pain, C. F. 1978: Late Quaternary land surfaces and geomorphic changes in the Rotorua Basin, North Island, New Zealand. *New Zealand journal of science* 21: 249-264.
- Kohn, B. P. 1979: Identification and significance of a late Pleistocene tephra in Canterbury district, South Island, New Zealand. *Quaternary research* 11: 78-92.
- Lowe, D. J. 1981: Origin and composite nature of late Quaternary airfall deposits, Hamilton Basin, New Zealand. Unpublished M.Sc. thesis, University of Waikato Library, Hamilton, New Zealand.
- 1985: Application of impulse radar to continuous profiling of tephra-bearing lake sediments and peats: an initial evaluation. *New Zealand journal of geology and geophysics* 28: (this issue).

- Lowe, D. J.; Hogg, A. G. in press: Tephrostratigraphy and chronology of the Kaipo Lagoon, an 11,500 year-old montane peat bog in Urewera National Park, New Zealand. *Journal of the Royal Society of New Zealand* 16 : (1986).
- Lowe, D. J.; Hogg, A. G.; Green, J. D.; Boubée, J. A. T. 1980: Stratigraphy and chronology of late Quaternary tephra in Lake Maratoto, Hamilton, New Zealand. *New Zealand journal of geology and geophysics* 23 : 481–485.
- Mackereth, F. J. H. 1966: Some chemical observations on post-glacial lake sediments. *Philosophical transactions of the Royal Society* 250 : 165–213.
- Mathewes, R. W.; Westgate, J. A. 1980: Bridge River tephra: revised distribution and significance for detecting old carbon errors in radiocarbon dates of limnic sediments in southern British Columbia. *Canadian journal of earth sciences* 17 : 1454–1461.
- McCraw, J. D. 1967: The surface features and soil pattern of the Hamilton Basin. *Earth science journal* 1 : 59–74.
- McGlone, M. S. 1983: Holocene pollen diagrams, Lake Rotorua, North Island, New Zealand. *Journal of the Royal Society of New Zealand* 13 : 53–65.
- McGlone, M. S.; Topping, W. W. 1977: Aranuiian (post-glacial) pollen diagrams from the Tongariro region, North Island, New Zealand. *New Zealand journal of botany* 15 : 749–760.
- 1983: Late Quaternary vegetation, Tongariro region, central North Island, New Zealand. *New Zealand journal of botany* 21 : 53–76.
- McGlone, M. S.; Nelson, C. S.; Hume, T. M. 1978: Palynology, age and environmental significance of some peat beds in the Upper Pleistocene Hinuera Formation, South Auckland, New Zealand. *Journal of the Royal Society of New Zealand* 8 : 385–393.
- McGlone, M. S.; Nelson, C. S.; Todd, A. J. 1984a: Vegetation history and environmental significance of pre-peat and surficial peat deposits at Ohinewai, Lower Waikato lowland. *Journal of the Royal Society of New Zealand* 14 : 233–244.
- McGlone, M. S.; Howorth, R.; Pullar, W. A. 1984b: Late Pleistocene stratigraphy, vegetation and climate of the Bay of Plenty and Gisborne regions, New Zealand. *New Zealand journal of geology and geophysics* 27 : 327–350.
- Moss, B. 1980: Ecology of freshwaters. Oxford, Blackwell Scientific Publications. 332 p.
- Nairn, I. A. 1980: Source, age, and eruptive mechanisms of Rotorua Ash. *New Zealand journal of geology and geophysics* 23 : 193–207.
- Pennington, W. 1981: Records of a lake's life in time: the sediments. *Hydrobiologia* 79 : 197–219.
- Pigott, C. D.; Pigott, M. E. 1963: Late-glacial and post-glacial deposits at Malham, Yorkshire. *New phytologist* 62 : 317–334.
- Pullar, W. A.; Birrell, K. S. 1973: Age and distribution of late Quaternary pyroclastic and associated cover deposits of the Rotorua and Taupo area, North Island, New Zealand. *New Zealand soil survey report* 1.
- Pullar, W. A.; Heine, J. C. 1971: Ages, inferred from ¹⁴C dates, of some tephra and other deposits from Rotorua, Taupo, Bay of Plenty, Gisborne and Hawke's Bay districts. *Proceedings Radiocarbon Users' Conference, Lower Hutt* : 117–138.
- Pullar, W. A.; Birrell, K. S.; Heine, J. C. 1973: Named tephra and tephra formations occurring in the central North Island, with notes on derived soils and buried paleosols. *New Zealand journal of geology and geophysics* 16 : 497–518.
- Sarna-Wojcicki, A. M.; Bowman, H. R.; Meyer, C. E.; Russell, P. C.; Woodward, M. J.; McCoy, G.; Rowe, J. J. jun.; Baedeker, P. A.; Asaro, F.; Michael, H. 1984: Chemical analyses, correlations, and ages of Upper Pliocene and Pleistocene ash layers of east-central and southern California. *U.S. Geological Survey professional paper* 1293. 40 p.
- Schofield, J. C. 1965: The Hinuera Formation and associated Quaternary events. *New Zealand journal of geology and geophysics* 8 : 772–791.
- Stewart, R. B.; Neall, V. E. 1984: Chronology of paleoclimatic change at the end of the last glaciation. *Nature* 311 : 47–48.
- Street, F. A.; Grove, A. T. 1979: Global maps of lake-level fluctuations since 30 000 yr B.P. *Quaternary research* 12 : 83–118.
- Topping, W. W. 1973: Tephrostratigraphy and chronology of late Quaternary eruptives from the Tongariro Volcanic Centre, New Zealand. *New Zealand journal of geology and geophysics* 16 : 397–423.
- Vucetich, C. G.; Howorth, R. 1976a: Proposed definition of the Kawakawa Tephra, the c. 20 000 years B.P. marker horizon in the New Zealand region. *New Zealand journal of geology and geophysics* 19 : 43–50.
- 1976b: Late Pleistocene tephrostratigraphy in the Taupo district, New Zealand. *New Zealand journal of geology and geophysics* 19 : 51–69.
- Vucetich, C. G.; Pullar, W. A. 1969: Stratigraphy and chronology of late Pleistocene volcanic ash beds in central North Island, New Zealand. *New Zealand journal of geology and geophysics* 12 : 784–837.
- Walker, D. 1970: Direction and rate in some British post-glacial hydrosere. Pp. 117–139 in: Walker, D.; West, R. G. ed. *Studies in the vegetational history of the British Isles*. Cambridge, University Press.
- Wells, B. W.; Boyce, S. G. 1953: Carolina Bays: additional data on their origin, age and history. *Journal of the Elisha Mitchell Scientific Society* 69 : 119–141.