PART 1 THE BASIS FOR LAKE DIVERSITY

1 Origins and development of the lakes

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INTRODUCTION

Because of a turbulent and complex recent geological history, New Zealand has an impressively diverse and dynamic landscape, and a correspondingly wide array of lake types, within a small land area (Irwin 1975a; Soons & Selby 1982;). The development of such an active geological environment in New Zealand has been governed largely by its location athwart the Australian and Pacific plate boundary, and its maritime mid-latitude position has made it particularly sensitive to the climatic fluctations and associated glaciations and sea level changes of the Quaternary Period (Suggate et al. 1978). At present, the rates of uplift and erosion of mountainous areas are among the fastest in the world. Earthquakes are common, and volcanism has characterised much of the North Island during the Quaternary with numerous volcanoes active in the last few thousand years. Large, explosive caldera volcanoes in central North Island have erupted repeatedly over the last million years, producing voluminous amounts of lava and widespread pyroclastic deposits. The landforms, soils and lakes are thus typically youthful, almost all being younger than two million years; indeed, much of the landscape is of late Pleistocene and Holocene age, and is still actively developing (Pillans et al. 1982).

Our purpose in this chapter is to outline the relationship between these often violent and spectacular geological processes which have led to the formation and development of the various lake types in New Zealand. Against this background we describe the classification and distribution of the main lake types, their ages and mechanisms of formation. We also comment on lake sedimentation patterns, palaeolimnological studies, and on features of lake bathymetry and morphology.

THE GEOLOGICAL ENVIRONMENT

Plate tectonic setting and deformation

The islands of New Zealand are the small emergent parts of a much larger submarine continental mass (Fig. 1) that was rafted away from Australia and Antarctica by sea-floor spreading in the proto-Tasman Sea between 80 and 60 million years ago (Weissel & Hayes 1977; Kamp 1986a). Much of this New Zealand subcontinent, especially that lying to the northwest and

southeast of New Zealand, is remnant from the former eastern margin of Gondwanaland, the ancient supercontinent of the Southern Hemisphere. The convergence (collision) of the Pacific and Australian lithospheric plates (Fig. 1) is marked by seismically active volcanic arcs that bisect the New Zealand subcontinent and landmass Cole (1986). This volcanism and associated earthquakes illustrate New Zealand's position as part of the Circum-Pacific Mobile Belt; the so-called "Pacific Ring of Fire".

The geological development of New Zealand during the Quaternary Period (the last 2 million years), and thus its present-day landscape and development of inland waters, have been greatly influenced by the movements associated with these plate tectonics (Suggate 1982). The relative movement of the Pacific and Australian plates at rates of 30-70 mm year ^{1} (Fig. 1; Walcott 1978) has resulted in crustal shortening and consequently regional uplift and subsidence. This has been accompanied by faulting and folding, commonly forming a basin-and-range topography, and is the ongoing "mountain building" period known in New Zealand as the Kaikoura Orogeny (Suggate et al. 1978). Crustal deformation is particularly intensive in a 70-100 km-wide zone running northeast-southwest through New Zealand from Hawke's Bay, through the Southern Alps, to Fiordland (Walcott 1984; Adams 1985), and shallow earthquakes occur frequently (Eiby 1975; Reyners 1984). Uplift rates are variable but generally fast (>2 mm year^{-1}; Fig. 2A), and in the Mt. Cook (3764 m a.s.l.) region in the central Southern Alps may approach 20 mm year^{-1} (Wellman 1979; Adams 1980; Crozier et al. 1982). Such rates indicate that most of the elevation of the South Island mountain ranges may have been attained in only the last few million years (Walcott 1978; Wellman 1979), and in the eastern North Island in perhaps only the last million years (Kamp 1982). A good example of the effect of this movement upon one of New Zealand's largest lakes is shown in Fig. 2B, for Lake Tekapo. Raised beaches and flights of marine terraces along many parts of the New Zealand coastline also attest to this tectonic uplift, together with the interplay of repeated sea-level fluctations. The terraces are best preserved along the Wanganui and Taranaki coasts, the east coast of the North Island from Bay of Plenty to Wellington, and the Canterbury and West Coast of the South Island (Chappell 1975; Ghani 1978; Suggate et al. 1978; Pillans 1983; Ota et al. 1984).

In addition to vertical movements, there have also been considerable lateral movements in New Zealand. For example, the Alpine Fault running along the length of the South Island, (Fig. 1) a major Fault similar in size to the San Andreas fault in California, and has accommodated about 480 km of horizontal displacement in the past 23 million years or so (Kamp 1986b).

Volcanism

Volcanic and associated activity has occurred through New Zealand's geological history but has been particularly important in late Tertiary and Quaternary times (i.e., the past 20 million years), chiefly in the North Island (Fig. 3). Frontal arc (andesitic) volcanoes have migrated southeastwards from Northland since about 20 million years ago, associated with gradual "sinking" of the subducting Pacific plate slab beneath the North Island (Kamp 1984; Brothers 1984), until reaching the present-day locus of activity in the Taupo Volcanic Zone (TVZ) in the central North Island (Fig. 4) about a million years ago (Wilson et al. 1984).

The TVZ is a narrow (<50 km), complex, volcanotectonic depression comprising a marginal basin and an andesitic arc, and extends about 250 km southwest from White Island in the Bay of Plenty to Mt. Ruapehu (2797 m) south of Lake Taupo (Fig. 4; Cole 1979, 1986). The andesitic volcanoes at the northern and southern ends of the TVZ are continuously active, all having erupted many times since European settlement, particularly Mt. Ngauruhoe (2290 m), a subsidiary cone of Mt. Tongariro (1968 m) (Cole & Nairn 1975; Plate 1). The central part of the TVZ, which is comparable in size and longevity to the Yellowstone volcanic area in the United States (Wilson et al. 1984), has erupted large quantities ($>10^4$ km^3) of mainly rhyolitic material as lava and pyroclastic deposits (ignimbrites and tephras) (Healy 1982). Most of these

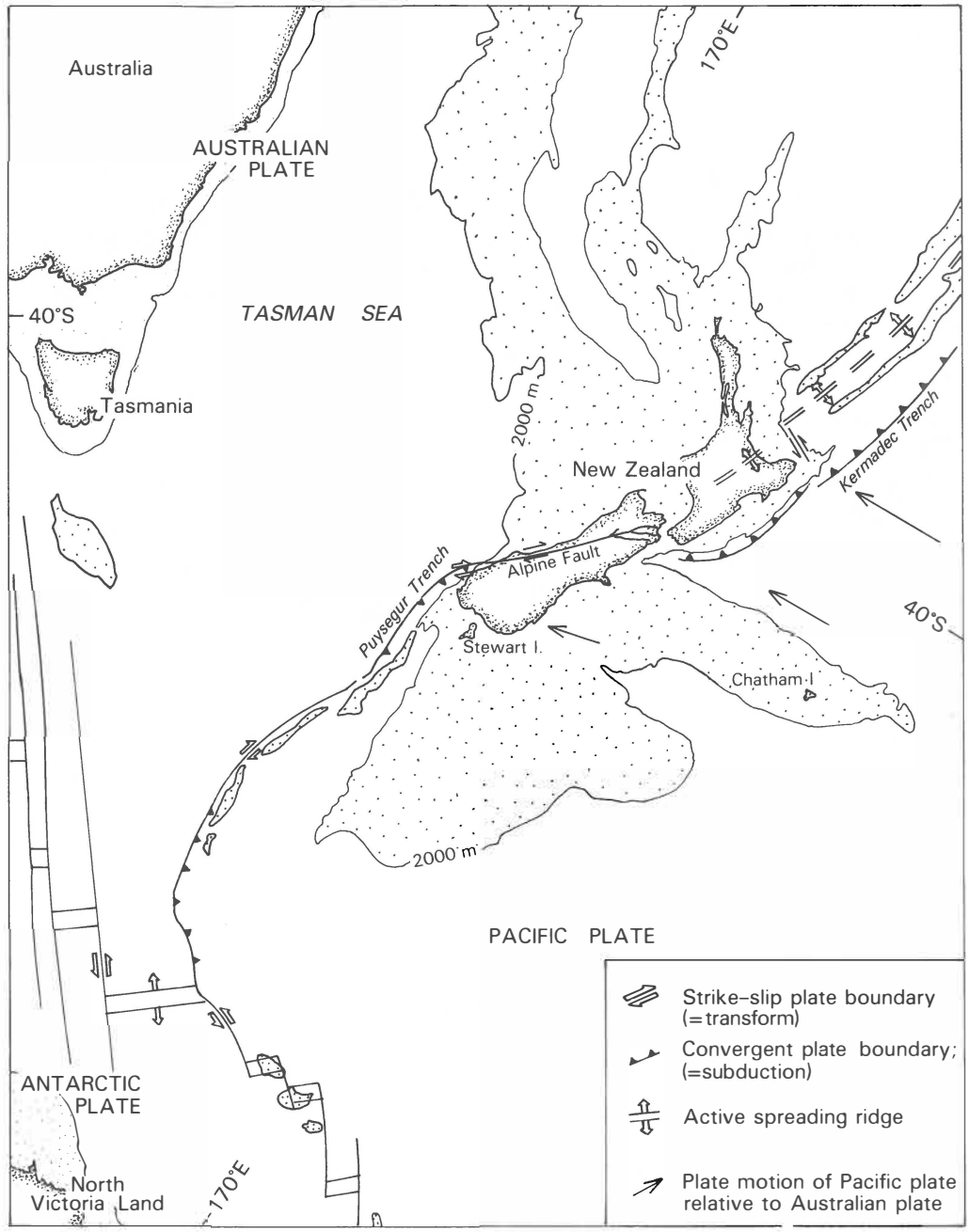
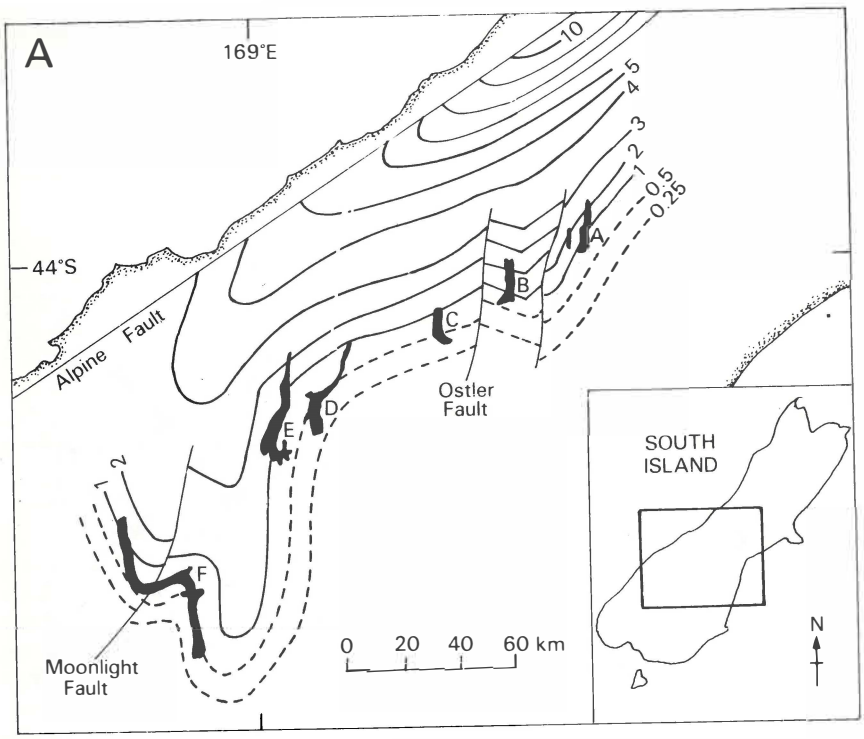


Fig. 1 Plate tectonic setting of New Zealand and the southwest Pacific showing the three major crustal plates and the main structural features associated with their boundaries. Sparse stipple represents continental sea floor shallower than 2000 m, and defines the New Zealand subcontinent. (After Kamp 1984, p.243 and Walcott 1984, p.2.)



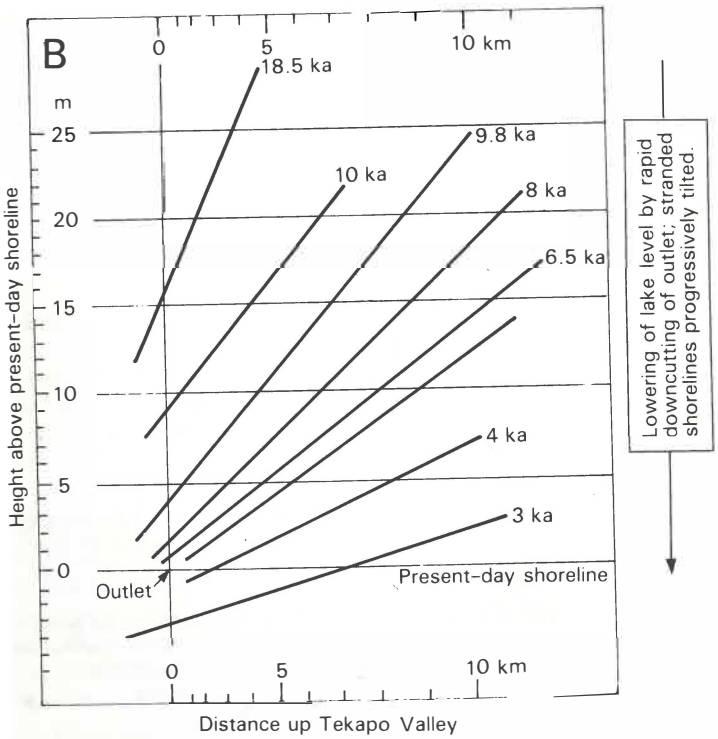


Fig. 2A The southern part of the Southern Alps showing estimated uplift rates in mm yr $^{-1}$. Lakes are: A, Tekapo and Alexandrina (left); B, Pukaki; C, Ohau; D, Hawea; E, Wanaka; F, Wakatipu.

B Graphs to show the progressively changing height of the shoreline along the length of Lake Tekapo, with outlet end (Tekapo River) at left. The numbered sloping lines are inferred tilted shorelines; numbers give ages in thousands of years ago (ka). Rapid outlet downcutting is assumed to have started 10 000 years ago when the glacier retreated up the lake (see text under Glacial lakes). (After Wellman 1979, pp.15 & 17.)

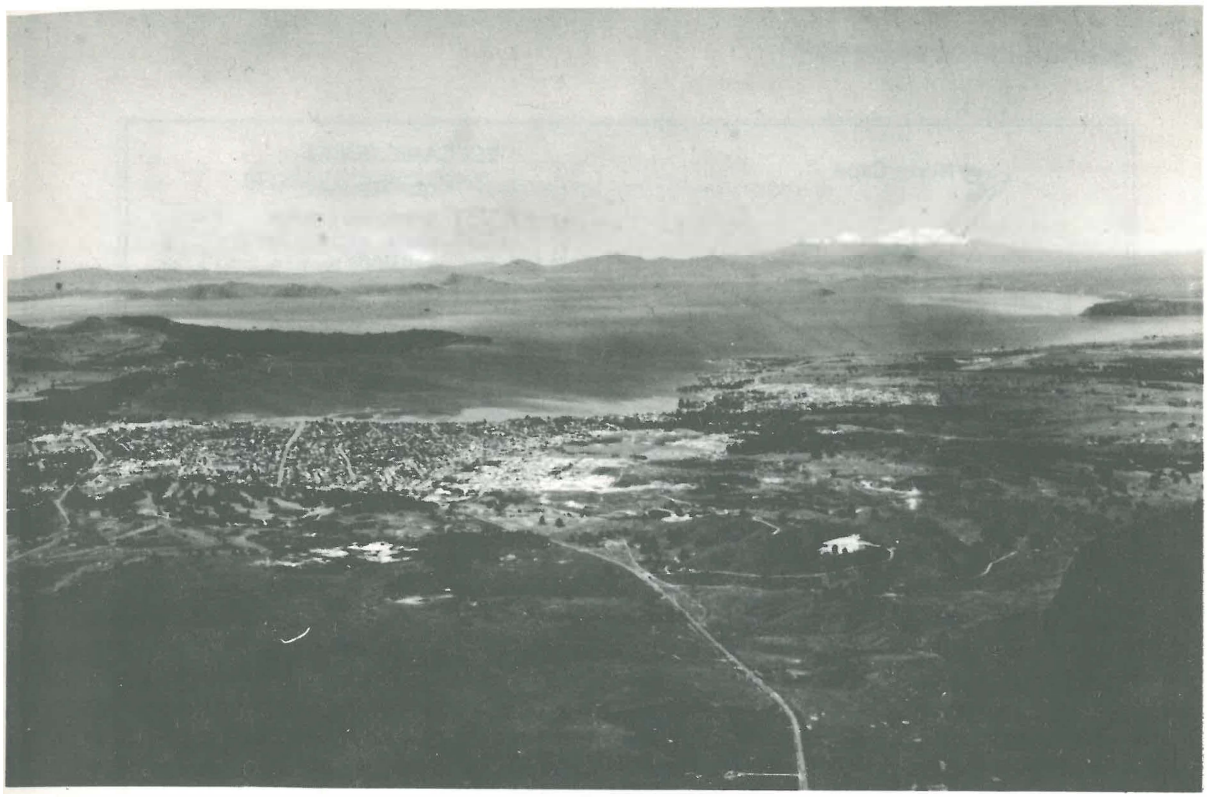


Plate 1 Lake Taupo, the largest lake in New Zealand (623 km²), the lake basin occupies the central part of the Taupo Volcano (see Fig. 8), an "inverse" volcano in which successive rhyolitic eruptions have typically been so powerfully explosive that the accumulation of material about the vent was insufficient to counterbalance the subsidence caused by magma withdrawal (Wilson & Walker 1985). The latest eruption, the Taupo Pumice eruption, took place c.1800 years ago from a vent within the lake near Horomatangi Reefs, and the modern lake dates from then. To the south (background) are the andesitic cones of Tongariro, Ngauruhoe, and Ruapehu making up the Tongariro Volcanic Centre. *Photo: National Publicity Studios, Wellington.*

materials have emanated from six large, multivent calderas (Fig. 4), some of which are classical "inverse" volcanoes that reflect extremely violent eruptions (Walker 1980, 1984). The basin of Lake Taupo is a fine example (Plate 1) of such volcanoes. The Mangakino and Kapenga Calderas are probably extinct, Rotorua and Maroa may be feebly active, and Taupo and Okataina are very active, the latest eruptions occurring c.1800 years ago and in A.D. 1886, respectively (Table 1) (Wilson et al. 1984; Walker et al. 1984; Wilson & Walker 1985). Very large, welded ignimbrite-producing eruptions from these calderas have a mean recurrence interval of c.30 000 years. One such eruption, that of the supervoluminous Whakamaru Ignimbrite and its postulated tephra fallout component, the Mt. Curl Tephra, produced more than c.1200 km³ of pyroclastic material (Froggatt et al. 1986). (By contrast, the recent Mt. St. Helens 1980 eruption in the USA produced about 1 km³.) This is the largest documented eruption from the TVZ, and one of the largest late Quaternary eruptions known; the quantity of fine ash and sulphur ejected into the stratosphere may have exceeded the amounts of dust currently postulated for nuclear explosion scenarios (Froggatt et al. 1986). During the past c.50 000 years there have been 33 rhyolitic eruptions generating nonwelded ignimbrites and widely distributed tephras from the Taupo and Okataina calderas alone, a mean rate of one every 1500 years (Table 1). Three of these eruptions produced c.100 km³ or more of pyroclastic material.

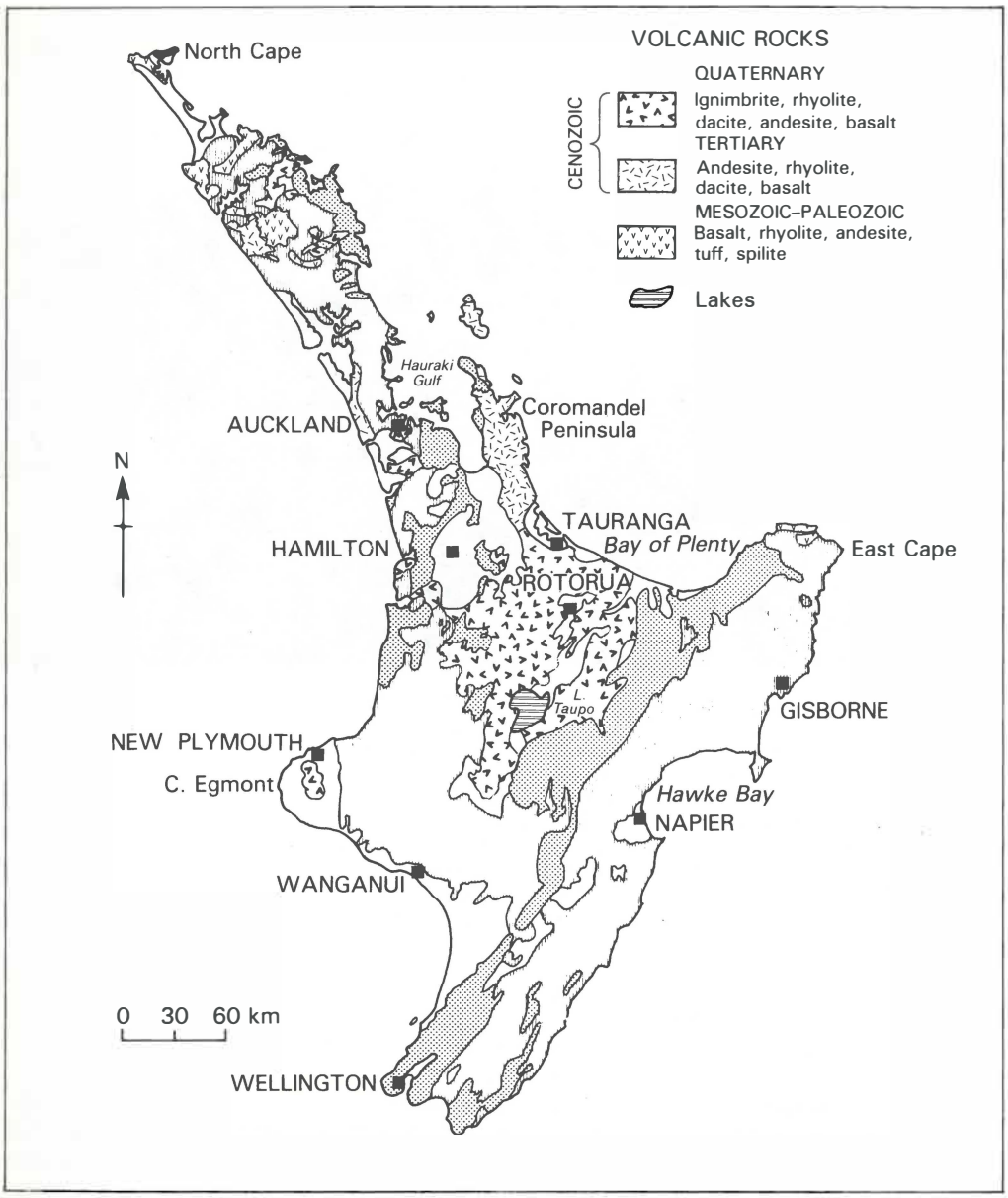
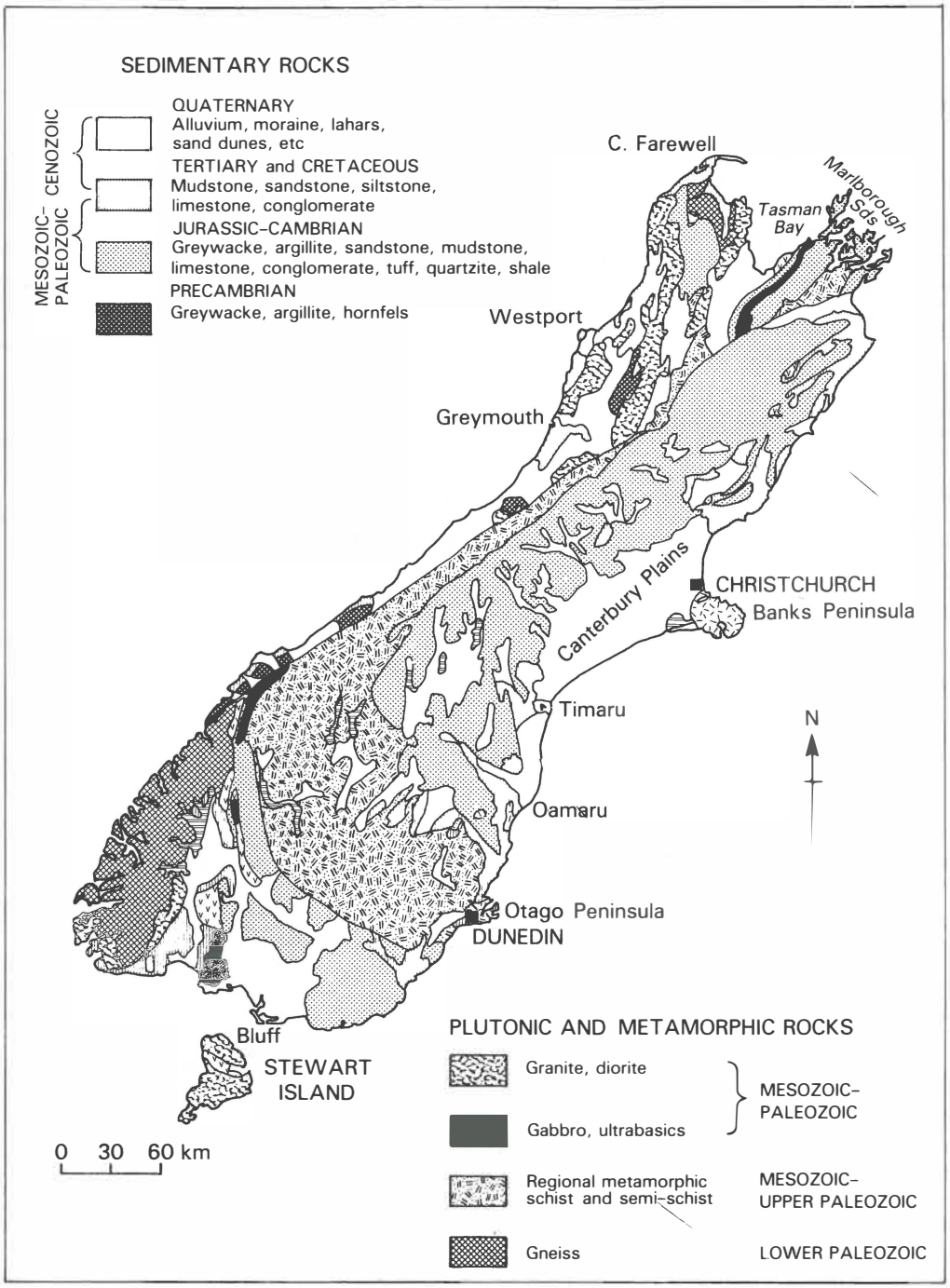


Fig. 3 Simplified geology of New Zealand. The map does not show surficial airfall deposits (loess, tephra) that blanket much of the landscape (McCraw 1975). Approximate geological time scale (millions of years ago) is: Quaternary 0-2 (Holocene 0-0.01, Pleistocene 0.01 - 2), and Tertiary 2 - 65 (= Cenozoic); Cretaceous 65 - 135, and Jurassic - Triassic 135 -230 (= Mesozoic); Permian-Devonian 230 - 390 (Upper Paleozoic); Silurian - Cambrian 390 - 570 (Lower Paleozoic); Precambrian pre-570. (After Stevens 1980, pp. 238-239 and maps in Suggate et al. 1978.) The geology and glacial history of New Zealand's Antarctic territory, the Ross Dependency, is broadly covered by Gunn & Warren (1962), Wilson (1978), and Barrett & McKelvey (1981).


SEDIMENTARY ROCKS
MESOZOIC–CENOZOIC
PALEOZOIC
QUATERNARY
Alluvium, moraine, lahars, sand dunes, etc
TERTIARY and CRETACEOUS
Mudstone, sandstone, siltstone, limestone, conglomerate
JURASSIC–CAMBRIAN
Greywacke, argillite, sandstone, mudstone, limestone, conglomerate, tuff, quartzite, shale
PRECAMBRIAN
Greywacke, argillite, hornfels
C. Farewell
Marlborough Sds
Tasman Bay
Westport
Greymouth
Canterbury Plains
CHRISTCHURCH
Banks Peninsula
Timaru
N
Oamaru
Otago Peninsula
DUNEDIN
Bluff
STEWART ISLAND
0 30 60 km
PLUTONIC AND METAMORPHIC ROCKS
Granite, diorite
Gabbro, ultrabasics
MESOZOIC–PALEOZOIC
Regional metamorphic schist and semi-schist
MESOZOIC–UPPER PALEOZOIC
Gneiss
LOWER PALEOZOIC

Faulting and subsidence accompanied by volcanism in the central part of the TVZ, forming a series of deep basins (underlying basement rocks are >3 km below sea level). The basins have been infilled with pyroclastic deposits and various sediments, including abundant diatomite. Drillhole and other evidence indicates that lakes have always been a prominent feature of the T.V.Z (e.g., Pain & Pullar 1975; Healy 1982), with much of the central TVZ being occupied by a large lake during the past c.300 000 years (Wilson et al. 1984).

Other volcanic centres outside the TVZ that have been active in the past thousand years or so are shown in the inset of Fig. 4 (Cole & Nairn 1975; Smith 1986). Mt. Egmont, an andesitic cone (2518 m) in Taranaki, has experienced at least four eruptions in the past 600 years, the latest being in c.A.D. 1755 (Neall et al. 1986). In the Auckland Volcanic District, which comprises 48 basaltic vents, Rangitoto Island is the largest and most recently active volcano (Kermode 1986). It last erupted possibly only c.200 years ago. Basaltic cones at Te Puke in the Bay of Islands-Kaikohe Volcanic District may have erupted c.1000 years ago. The offshore rhyolitic volcano of Mayor Island, in the Bay of Plenty (Fig. 4), probably last erupted <c.1000 years ago (Buck et al. 1981).

Table 1 Stratigraphy, approximate ages, and volumes of major tephras and ignimbrites erupted from Taupo and Okataina volcanoes since about 50 000 years ago. All are rhyolitic except Tarawera which is of basaltic composition. (After Howorth 1975; Vucetich & Howorth 1976; Froggatt 1982; Walker etal. 1984 some dates after Green & Lowe 1985 and Lowe & Hogg 1986.)

Taupo Volcano			Okataina Volcano		
Tephra	Years B.P.	Vol. (km^3)	Tephra	Years B.P. †	Vol. (km^3)
			Tarawera	A.D.1886	2
Taupo Lapilli		⩾12 (70)*	Kaharoa	700	4
Rotongaio Ash	1800	1	Whakatane	4800	6
Hatepe Lapilli		2	Mamaku	7000	6
(Taupo Pumice)			Rotoma	8500	12
Mapara	2200	2	Waiohau	12 000	18
Whakaipo	2800	1.5	Rotorua	13 300	7
Waimihia	3200	14 (5)	Rerewhakaaitu	14 700	7
Hinemaiaia	4500	3	Okareka	17 000	8
Motutere	5400	0.5	Te Rere	19 000	9
Opepe	8800	4	Omataroa	28 000	16 (5)
Poronui	9900	3	Awakeri	30 000	2
Karapiti	10 000	2	Mangaone	31 000	16 (6)
Kawakawa	20 000	70 (100)	Hauparu	c.36 800‡	10
Te Mahoe	c.37 000	0.3	Te Mahoe	c.37 000	0.3
Poihipi	21 000	<1	Maketu	c.37 200‡	15
Okaia	22 000	5-7	Tahuna	c.38 000‡	3
Tihoi	c.38 000‡	<5	Ngamotu	c.38 500‡	2
Waihora	c.39 000‡	<1	Ṛotoehu	c.50 000‡	90 (150)
Otake	c.40 000‡	<2			

* Volumes in parentheses are estimates of ignimbritic components of eruptions.

† Except as noted.

‡Tihoi to Otake eruptions may be aged c.45 000–50 000 yr B.P. (Wilson et al. 1986); Hauparu to Ngamotu eruptions c.40 000–45 000 yr B.P. (McGlone etal. 1984a).

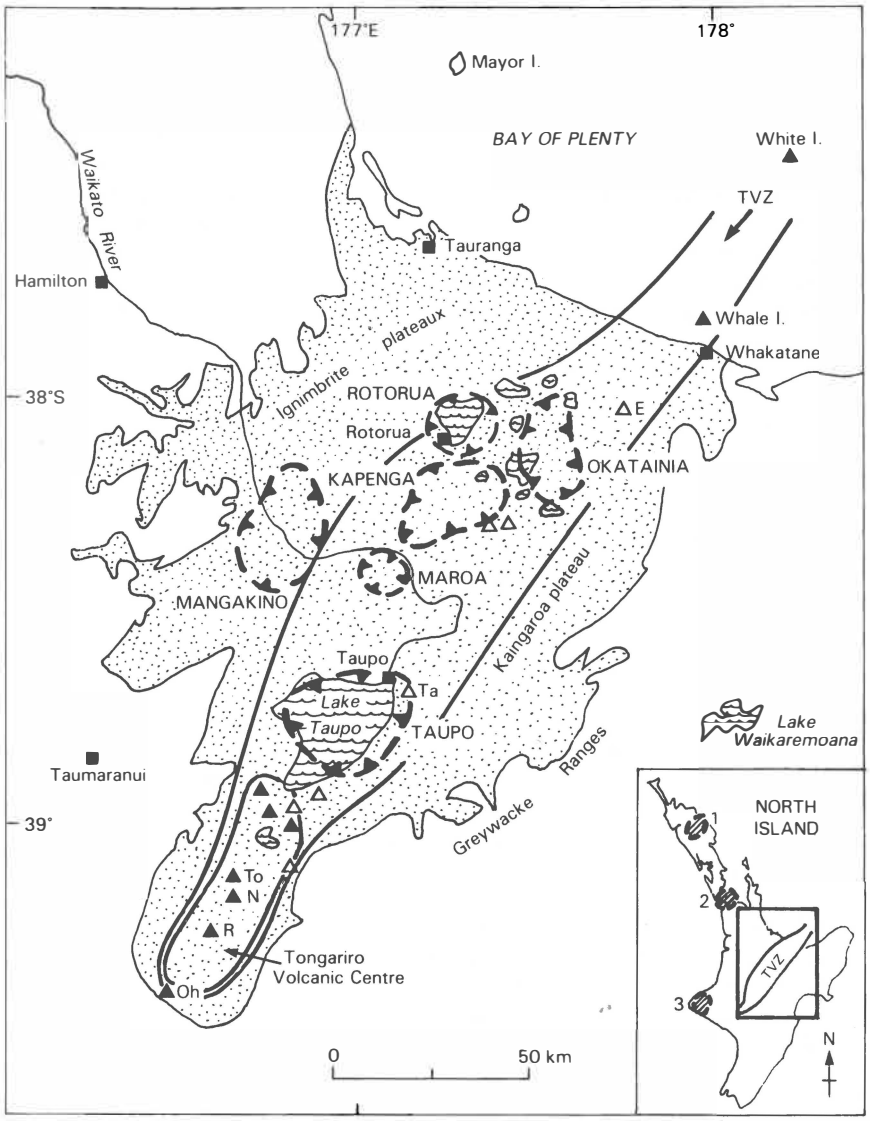


Fig. 4 The central volcanic region (stippled) showing the six multivent rhyolitic calderas/volcanic centres (barbed dashes; names in capitals) in the central part of the Taupo Volcanic Zone (TVZ) (note: the northwestern boundary of the TVZ is not well defined geophysically – see Stern 1986). Closed triangles = andesitic volcanoes; open triangles = dacitic volcanoes. E = Mt. Edgecumbe; Ta = Mt. Tauhara; To = Mt. Tongariro; N = Mt. Ngauruhoe; R = Mt. Ruapehu; Oh = Ohakune. The inset shows other volcanic districts outside the central volcanic region. 1, Bay of Islands-Kaikohe; 2, Auckland; 3, Egmont (note: Mt Egmont is also known as Mt. Taranaki). (After Cole & Nairn 1975, p.11; Cole 1979, p.634; and Wilson et al. 1984, p.8464.)

Glaciation, erosion, and aggradation

While volcanism has characterised the North Island during the Quaternary, the successive periods of cold climate and glaciations associated with the current "Ice Age" (e.g., see Bowen 1978) have had their greatest influence in the South Island. The rapid tectonic uplift of the Southern Alps produced elevated areas for snow accumulation and the relief and structural features neces-

sary for the major valley glacier systems to develop during the glaciations. Recent deep-sea drilling offshore from New Zealand (Nelson et al. 1985) has shown these repeated glaciations to be virtually synchronous with the continental glaciations (ice sheets) that have occurred in the Northern Hemisphere over the past 2.4 million years (Shackleton & Opdyke 1977). The latest glacial stage in New Zealand (oxygen isotope stage 2) was at its maximum c.18 000 years ago (Wilson 1978; Nelson et al. 1985). Sea level dropped to c.100 m or more below its present level, hence the three main islands of New Zealand were contiguous at that time (Fig. 5).

In much of the South Island, the snowline dropped c.1000 m and mean temperatures were about 4 to 6 °C lower than present (Wilson 1978; Fleming 1979; Peterson et al. 1979). Complexes of large, often coalescing valley glaciers and alpine ice caps covered most, but not all, of the Southern Alps and parts of Stewart Island (Fig. 5; Burrows 1979; Gage 1980; Soons 1982). Today's modern (interglacial) valley glaciers such as Tasman, Franz Joseph, and Fox occupying valley heads in the Southern Alps are only small remnants of those of the last glaciation (Gage 1980).

The areas most extensively glacierised in the South Island were the West Coast and Fiordland, a consequence of their rapid tectonic uplift, hence high relief and very high precipitation (Soons 1982). Much of the alpine landscape here and elsewhere in the Southern Alps consists of large, over-deepened valleys with steep sides and hanging valleys, and reflects large-scale glacial erosion (Soons & Selby 1982). During the periods of glacial advance and retreat, erosion debris of glacial drift and outwash gravels was deposited in huge quantities in inland basins and on both coastlines (e.g., in central Otago and Westland and the Canterbury Plains, Fig. 5; N.Z. Geological Survey 1973; Fitzharris et al. 1982; Soons 1982).

By comparison with the South Island, glaciation in the North Island was limited to largely periglacial activity with severe fluvial and wind erosion. Mean temperatures in southern and central North Island dropped by about 4 to 5 °C during the glacial maximum (Hendy & Wilson 1968; McGlone et al. 1978; Peterson et al. 1979; McGlone 1983a; McGlone & Topping 1983), but in northern North Island may have been only about 2 °C lower than present (Wilson 1978). Erosion detritus mixed with fresh volcanic material was deposited in lowlands in the North Island (Fig. 5), particularly in an extensive alluvial fan (the Hinuera Formation) in the Waikato region at, or just after, the height of the last glaciation (Schofield 1965; Hume et al. 1975; McGlone et al. 1978).

Overall, the dominantly hilly and often mountainous nature of much of New Zealand, coupled with a high rainfall and the widespread occurrence of highly jointed basement rocks and soft sedimentary cover rocks (e.g., mudstones) (Fig. 3) that are very susceptible to erosion, has produced generally fast rates of denudation (10^2–10^3 m^3 km^{-2} $year^{-1}$, particularly through landsliding (Adams 1980; Crozier et al. 1982; O'Loughlin & Pearce 1982; Pearce & Watson 1986).

Dunes and coastal barriers

The accumulation at New Zealand's coastline of large quantities of gravelly and sandy sediment from the glacial and fluvial erosion and volcanic activity during glaciations (especially the latest glacial stage) has led to a relatively high proportion of sand-gravel beaches and large, recently formed dune ridges, sandy barriers, and spits along the modern shore line (McLean 1978; Healy & Kirk 1982). Dunes are particularly common along the west coast of the North Island. Spits and barriers are common in northern and eastern parts of the North Island and in the northern South Island; gravel-pebble barriers occur in areas where there is a large gravel input into the littoral system as in the Canterbury and Westland areas in the South Island.

These coastal deposits have originated by various mechanisms, largely during the general postglacial rise in sea level over the past 10 000 years so (Healy & Kirk 1982; Gibb 1983) (see discussion below).

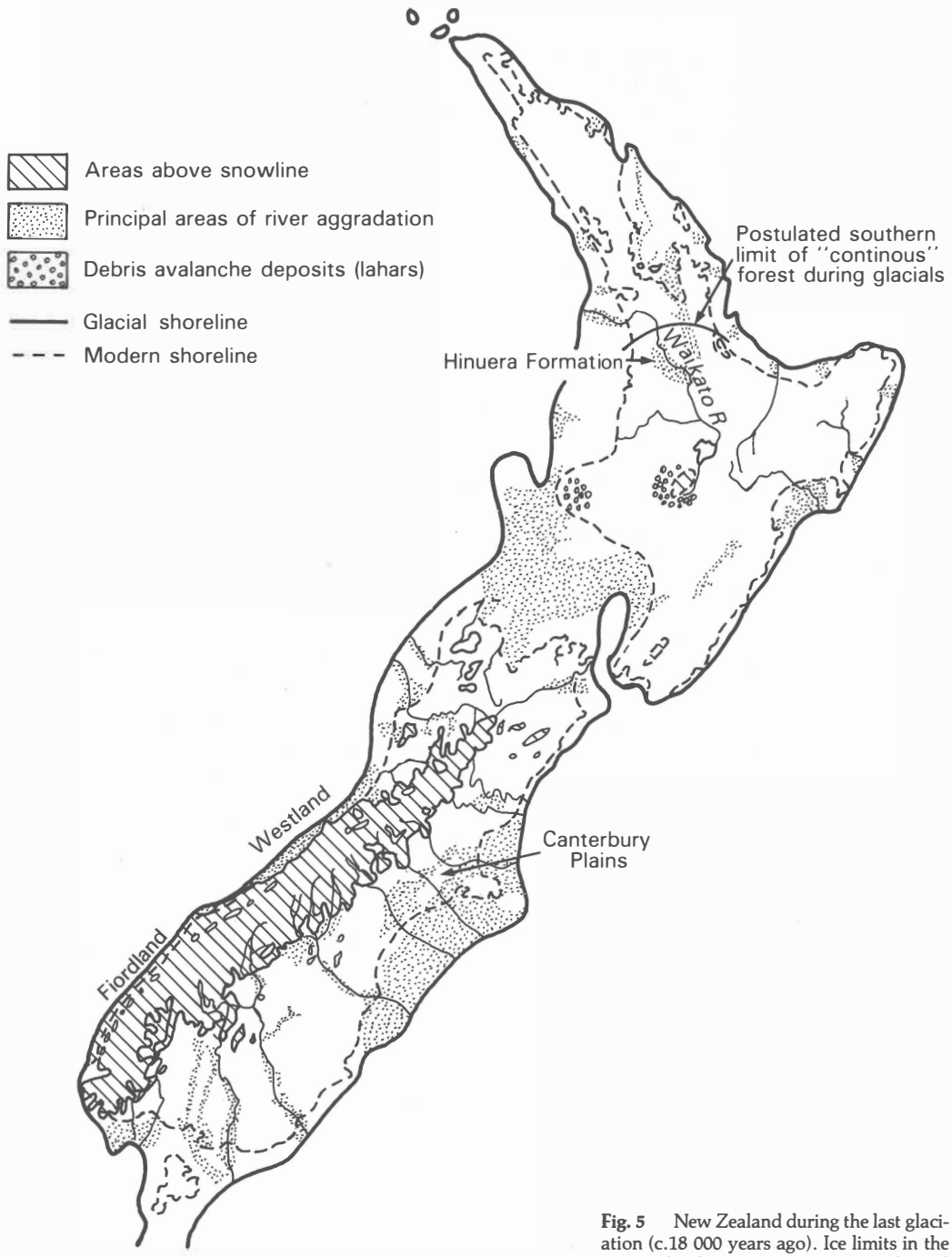


Fig. 5 New Zealand during the last glaciation (c.18 000 years ago). Ice limits in the North Island are uncertain (N.Z. Geological Survey 1973; McGlone 1983a). (After Fleming 1979, p.79, Suggate et al. 1978, p.741, and Wilson 1978, p.17.)

ORIGINS AND DEVELOPMENT OF THE LAKE BASINS

The variety and general modes of origin of New Zealand's lakes have been broadly known for some time. For example, Lucas (1904) noted the interesting heterogeneity of New Zealand lakes, and some information on lake origins is given in the older literature, particularly the various New Zealand Geological Survey bulletins (e.g., Park 1909; Ferrar 1934; Grange 1937; see also references in Irwin 1975a, and Suggate et al. 1978), and in Cotton (1958), and Gage (1959). More recent articles dealing with individual lakes or groups of lakes include Gage (1975), Healy (1975a), Irwin (1975b), Timperley (1983), and Green & Lowe (1985). Additional information may be inferred from other sources, mainly in the geological literature (e.g., Schofield 1975; Soons & Selby 1982). Much of this disparate information is reviewed here together with additional information.

Classification

Gage (1975) has argued that detailed classifications such as Hutchinson's (1957) scheme are fundamentally inappropriate for New Zealand's glacial lakes, most of which owe their origins to the combined action of a variety of the processes treated separately by Hutchinson. Parallel arguments regarding volcanic-tectonic lakes are put forward by Irwin (1975b), and this polygenesis certainly applies to some other lake types as well. Consequently, all classification systems that have been developed for New Zealand lakes use only a relatively small number of major subdivisions.

The major contributions to the development of a classification of the origins of New Zealand lakes have been by Irwin (1972a, 1975a, b), who has considered all New Zealand lakes; by Gage (1959, 1975) on South Island glacial lakes; Healy (1963, 1975a) on Rotorua area lakes; and by Bayly & Williams (1973) whose classification of lake origins includes many New Zealand examples. The most useful general account is that of Irwin (1975b). Based on this Irwin (1975a) compiled a checklist of all New Zealand lakes having major dimensions of 0.5 km or more, a total of nearly 800 lakes. The checklist was derived from topographic maps and includes information on the likely mode of origin, length, breadth, area, and altitude of each lake. Nearly 90% of the lakes were classified, on the basis of the origin of the lake basin, into nine broad categories corresponding largely to the major categories of Hutchinson (1957).

Table 2 Broad classification scheme for New Zealand lakes (acronyms for the categories are given in parentheses). (Modified after Irwin 1975a, b.)

Class	Lake Type
1	Tectonic basins, formed by earth movement (T)
2	Associated with volcanic activity (V)
3	Formed by glacial activity (includes Antarctic lakes) (G)
4	Formed by landslides (L)
5	In phytogenic basins (P)
6	Formed by or associated with rivers (R)
7	Formed by wind-blown dunes (W)
8	Barrier-bar lakes, associated with shorelines (B)
9	Associated with karst landscapes (K)
10	Man-made lakes (D)

The overall features of Irwin's (1975b) classification are retained here, but modified in the following ways:

(1) Included are a few small lakes associated with karst landscapes.

(2) Irwin's swamp group (e) is dispensed with as this is not a natural grouping but contains a heterogeneous selection of lakes that are probably late stages in the development of originally shallow lakes formed in various ways. For example, many small lakes in the Waikato region that Irwin classified as swamp lakes are primarily fluviatile in origin, and have been secondarily modified by later swamp and peat development around them (Green & Lowe 1985) (see below). Thus where possible we have attempted to reallocate these lakes into other groups, and have replaced the swamp group with a new category (lakes in phytogenic basins, equivalent to Hutchinson's types 69 and 70) whose basins are formed primarily by, or in, organic accumulations.

(3) We have linked the term "Barrier" to "Bar" for Irwin's shoreline category because it is perhaps genetically more appropriate (bar applying solely to submerged features, Healy & Kirk 1982). The modified classification is given in Table 2. We follow Hutchinson (1957) in that the primary modes of formation, hence classification, are taken to be those events that actually determined that the basins could hold water.

Because of the localised distribution of the major geological processes in New Zealand, and the close relationship between geological processes and geomorphological development as noted earlier, the major lake types are geographically grouped into distinct areas (Appendix A). Volcanic lakes are restricted to the North Island and most are found in the Taupo-Rotorua volcanic area (the TVZ); glacial lakes are restricted to the South Island*; wind-formed lakes occur mainly along the west coast of the North Island; and river lakes are most numerous on the flood plains of the major river systems. The frequency of the various lake types with respect to area is shown in Table 3; similar tables dealing with altitude are given in Irwin (1975a, p. 142). The North Island has a predominance of small (<5 km^2) wind and river-formed lakes, found mainly at low altitudes (<90 m a.s.l.) along the west coast and in the lower reaches of the river courses, respectively. Most of the volcanic lakes are found at altitudes of >275 m on the central volcanic plateau, and on the average are larger than the other lake types. By contrast, the South Island has a predominance of glacial lakes, mostly at altitudes >600 m. The majority of these glacial lakes are small, high country tarns, although the largest South Island lakes are also glacial and at lower altitudes (Appendix B). Wind-formed lakes are much less common than in the North Island (Table 3).

Tectonic lakes

Tectonic lake basins, formed wholly by movements of the earth's crust, are not strictly represented in New Zealand, although some lakes partly formed by displacement of the ground surface are known. Most of these occur in the seismically-active Hawke's Bay region in the North Island (Appendix A, area R4) (e.g., Lakes Hatuma, Poukawa, and Runanga: Lillie 1953; Kingma 1971; Froggatt & Howorth 1980; Harper et al. 1986). All are affected to some extent by river or peat deposits. Lake Wairarapa has previously been regarded as one of New Zealand's few tectonic lakes (Cotton 1958), but it is probably best described as a fluviatile lake (Leach & Anderson 1974; see below). Several South Island lake basins (e.g., Lakes Ellery, Kaurapataka, and Brunner) are thought to have been influenced to a small extent by faulting (Morgan 1911; Gage 1975).

Although definitive tectonic lakes are thus few, many other lakes in New Zealand have been formed as an indirect consequence of the country's pervasive tectonism (e.g., those formed by earthquake-induced landslides, and most volcanic lakes).

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* Most of the Dry Valley Lakes of New Zealand's Ross Dependency in Antarctica are also primarily due to glacial processes (see chapter 14).

Table 3A Area frequency of lake types in the North Island.* The list includes only those lakes with at least one axis ⩾0.5 km.† (Modified after Irwin 1975a.)

	Area (km²)						
Type	<0.5	0.5-5	5-50	50-500	500-5000	Total	%
Wind	88	18	-	-	-	106	35.3
River	50	13	3	1	-	67	22.3
Artificial	19	10	5	-	-	34	11.3
Volcanic	11	8	9	1	1	30	10.00
Landslide	13	4	-	1	-	18	6.0
Barrier-bar	11	2	1	-	-	14	4.7
Tectonic	2	4	-	-	-	6	2.0
Phytogenic	1‡	-	-	-	-	1	0.3
Karst	-	1	-	-	-	1	0.3
Glacial	-	-	-	-	-	0	0.0
Not determined	23	-	-	-	-	23	7.8
Totals	218	60	18	3	1	300	100.0
%	72.7	20.0	6.0	1.0	0.3		

Table 3B Area frequency of lake types in the South Island* The list includes only those lakes with at least one axis ⩾0.5 km.† (Modified after Irwin 1975a.)

	Area (km²)						
Type	<0.5	0.5-5	5-50	50-500	500-5000	Total	%
Glacial	181	86	15	9	-	291	61.1
River	44	9	1	-	-	54	11.3
Artificial	17	10	3	1	-	31	6.5
Landslide	7	12	1	-	-	20	4.2
Barrier-bar	13	2	2	1	-	18	3.8
Wind	13	-	-	-	-	13	2.7
Phytogenic	-	-	-	-	-	0	0
Tectonic	-	-	-	-	-	0	0
Volcanic	-	-	-	-	-	0	0
Not determined	45	4	-	-	-	49	10.4
Totals	320	123	22	11	0	476	100.0
%	67.3	25.8	4.6	2.3	0		

* Many lakes have complex origins hence some lake-type designations are uncertain. List includes Stewart Island, Mayor Island, and Ruapuke Island; lakes on other offshore islands and in the Ross Dependency (Antarctica) are excluded.

† Discussion in the text may include lakes of any size.

‡ Made up of small pools in bog c.1.5 km long (Kaipo Lagoon, App. A, L1).

Volcanic lakes

In many ways these lakes are the best known in New Zealand. All of them are found in three main areas, coinciding with the distribution of recent volcanism: the TVZ, the Auckland Volcanic District, and the Bay of Islands-Kaikohe Volcanic District (Fig. 4; Appendix A). Only one volcanic lake (Dive) occurs in the Egmonst Volcanic District (Table 4). Volcanic lakes are also found on some of the offshore islands (e.g., Mayor and Raoul Islands: Bayly et al. 1955; Buck et al. 1981; Lloyd & Nathan 1981). Most of the lakes in their present form are young, although lakes have probably occurred in all of these areas over long periods of time (Grange 1937; Healy 1975a; 1982).

In each area, lake basins have been formed by three major processes, acting singly or in combination (Healy 1975a):

(1) local explosive eruptions, producing craters;
(2) massive eruptions, producing large collapse calderas;
(3) blocking of valleys by lava flows or pyroclastic material.

In New Zealand, the largest volcanic lakes have been produced by (2) and (3) acting together and lie within the Rotorua, Okataina, and Taupo Calderas (Fig. 4). Faulting in conjunction with these processes is also frequently important (e.g., see Figs. 6 and 8 below; Grange 1937; Healy 1975a; Buck et al. 1981; Nairn 1981; Timperley 1983). The ages of the volcanic lakes have been determined chiefly by radiometric dating of the pyroclastic deposits erupted during the formation and development of the calderas and explosion craters (Table 4).

Lakes in the TVZ

Rotorua area lakes. The origin and development of lakes in the Rotorua area (Fig. 6; Appendix A, V1) is intimately connected with the history of volcanism in the Rotorua and Okataina volcanoes. Lake Rotorua lies in the Rotorua Caldera, a downsagged caldera formed c.140 000 years ago by the eruption of the Mamaku Ignimbrite (Healy 1982; Walker 1984). A lake formed soon after this eruption (Wood 1986). Lake level has fluctuated considerably and the highest stand occurred when the Rotoiti Breccia pyroclastic flows from the Okataina volcano c.50 000 years ago (McGlone at al. 1984a) blocked the northward drainage from Lake Rotorua. Extensive lacustrine terraces around the lake mark this high stand (Fig. 7; Kennedy et al. 1978). The sequence and extent of changes in the lake level and area since then (Fig. 7) have been governed largely by volcanic activity in the nearby Okataina volcano, as described by Healy (1975a), Kennedy et al. (1978), and Wood (1986). It is possible that the high lake levels between c.8000 and 4000 years ago were partly a result of greater rainfall than at present (McGlone 1983c). In recent times, the lake level has varied by c.1.4 m. This fluctuation in level is correlated mainly with variation in rainfall (as in other Rotorua area lakes) but also partly with siltation in the Ohau Channel outlet (Healy 1975b).

The origins of most of the other lakes in the Rotorua area are associated with the volcanic activity in the Okataina Volcanic Centre, comprising the Haroharo and Tarawera volcanic complexes within the Haroharo Caldera, plus adjacent sub-calderas of Rotoma and Okareka (Fig. 6; Healy 1975a; Nairn 1981, 1986). Lakes Tarawera, Okataina, and parts of Rotoiti and Rotoehu occupy marginal portions of the Haroharo Caldera, and were formed largely by lava damming (Plate 2). Lakes Okataina and Tarawera attained their present-day forms probably c.7000 and c.5000 years ago, respectively (Table 4; Nairn 1981). It is unlikely that they were once joined, as previously thought (Healy 1975a), although Okataina may have had a south-draining outlet into the Tarawera valley between c.7000-5000 years ago (Nairn 1981). A small lake, or lakes, probably occupied the Tarawera valley before the modern lake was formed. These and other "proto" lakes in the Rotorua area would have been periodically modified by the eruptions from the Tarawera and Haroharo volcanoes (Nairn 1981). The 1886 Tarawera eruption, for example, evidently resulted in a c.12 m rise in the level of Lake Tarawera through

Table 4 Ages of volcanic lakes in the TVZ and other volcanic districts in the North Island.

Lake	Age (1000 years B.P.)*	Main mode of origin and references
	Mayor Island	
Aroarotamahine Te Paritu	<c.1.0	Dammed by young lava dome (Buck et al. 1981)
	TVZ - Rotorua area	
Rotorua	c.140 (see also Fig. 7)	Caldera subsidence associated with eruption of Mamaku Ignimbrite (Healy 1975a; Kennedy et al. 1978; Wood 1986)
Okareka	c.19	Dammed by lavas associated with Te Rere eruptive episode (Nairn 1981)
Tikitapu (Blue) Rotokakahi (Green)	c.13.3	Dammed by lavas of Rotorua Ash eruptive episode (Nairn 1980, 1981)
Rotoma	c.8.5 - 9.0	Small caldera collapse associated with Rotoma eruptive episode (Nairn 1981, 1986; see also Healy 1975b)
Rotoiti Rotoehu	c.8.5 - 9.0	River valleys dammed by lavas associated with Rotoma eruptive episode (Healy 1975a; Nairn 1981)
Okataina	c.7.0	South-draining valley dammed by lavas of Mamaku eruptive episode; lake level possibly raised to present-day level c.5000 yr B.P. by lava flow of Whakatane eruptive episode (Nairn 1981)
Tarawera	c.5.0	Lake attained present form through damming of eastern drainage by lavas associated with Whakatane eruptive episode; valley probably contained small lake(s) since c.7000 yr B.P. or earlier (Nairn 1981, 1986)
Rotokawau Rotongata Rotoatua	c.3.0 - 4.0	Explosion craters associated with Rotokawau eruption (Grange 1937; Healy 1975a; Cole & Nairn 1975; Browne & Lloyd 1986)
Rerewhakaaitu	c.0.7	Dammed by Kaharoa pyroclastics (Nairn 1981); Awaatua Basin possibly formed in hydrothermal explosion c.12 kyr B.P. (Healy 1975a)
Okaro, Ngapouri (= Opouri), Ngahewa, Rotowhero, Tutaeinanga, Opal, Whangioterangi, Ngakoro, Orotu	c.0.7 - 0.9	Explosion crater eruptions along fault, possibly contemporaneous with Kaharoa eruption (Lloyd 1959; Cross 1963; Healy 1975a; Browne & Lloyd 1986)
Rotomahana (and Waimangu lakes – post A.D. 1886)	A.D. 1886	Mainly hydrothermal explosions near end of Tarawera eruption (Nairn 1979; Nairn et al. 1986; Lloyd 1986)

Lake	Age (1000 years B.P.)*	Main mode of origin and references
	TVZ - Taupo area	
Taupo	c.1.8 (c.A.D. 186)	Occupies calderas and grabens within Taupo Caldera (Fig. 8); modern lake formed after earlier lake emptied by Taupo Pumice eruption (Healy 1975a; Wilson et al. 1984; Northey 1986)
Rotokaua (Rotokawa)	c.5	Hydrothermal explosion crater (Cole & Nairn 1975)
Rotoaira	?>c.1.8.	Fault-bound basin adjacent to Tongariro and Pihanga lavas; floored by Taupo Pumice (Gregg 1960; Cole 1978; Froggatt 1981a lake level held by lava flow from Tongariro); Healy 1982
Rotopounamu	? <c.10	Explosion crater on Pihanga (fault-bound) (Gregg 1960; Cole 1978; Cole et al. 1986)
Blue	c.9.7	Explosion crater associated with eruption of Poutu Lapilli (Topping 1973; Cole & Nairn 1975)
Tama Lakes	c3.4 - 9.7	Explosion craters associated with eruption of Papakai Tephra or members of Mangamate Tephra, or both (Topping 1973; Cole & Nairn 1975)
Rangatau Lakes	? <c.10	Explosion craters, Ohakune (Cole 1978)
Emerald Lakes	c.1.2	Explosion vents associated with eruptions from Red Crater (post-Taupo Pumice) (Topping 1974; Cole & Nairn 1975)
Crater (Ruapehu)	Active vent	See Gregg (1960) and Cole & Nairn (1975)
	Auckland-Kaikohe-Bay of Islands	
Pupuke	⩾c.40	Explosion crater (maar) (^{14}C date >c.40 kyr; K/Ar age c. 36-42 kyr: Healy 1975a; Cole & Nairn 1975; Searle 1981; MacDougall et al. *in* Heming and Barnet 1986)
Western Springs	⩽c.28	Abuts lava from Mt. Eden (Fergusson & Rafter 1959; Johnstone 1972; Searle 1981)
Waiatarua (St John) (drained)	c.9.0	Dammed by lava from Mt Wellington (Searle 1981; D.J. Lowe & M.S. McGlone unpubl.)
Omapere	c.1.0	Present lake possibly formed by silting-up of outlet (see text); previously, lake existed intermittently after original valley drainage dammed by lava flows (Bell & Clarke 1909; Cotton 1958; Browne et al. 1981); oldest lake sediments are >c.40 kyr (Hogg et al. 1978)
Owhareiti	? <c.5	Dammed by lava from recent well-preserved cone (Poerua) (Kear 1961; Skinner *in* Browne et al. 1981.)
	Egmont	
Dive	≳c.3	Drainage dammed by Northern Beehive lava dome emplaced c.3 kyr or earlier (Neall 1971; V.E. Neall pers. comm. 1986); lake has been protected from infilling with pyroclastic and lahoric debris by a ridge to the north (Neall 1971)

* Except where noted as historical.

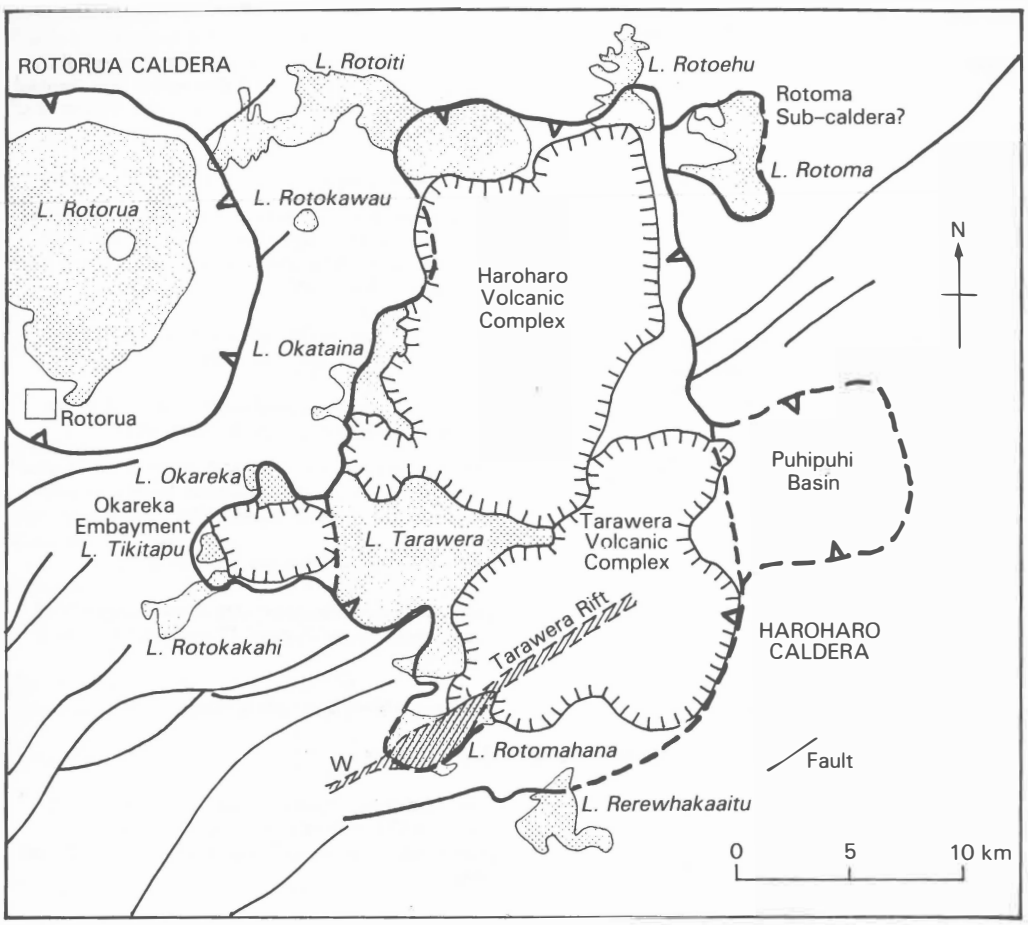


Fig. 6 The Rotorua area showing structural and volcanic features associated with the Rotorua Caldera and the Okataina Volcano (comprising Haroharo and sub-calderas), and their relationship to the major lakes. W = Waimangu hydrothermal area. (After Nairn 1981, p.145, and Nairn 1986, p.98.)

blocking of the Tarawera River outlet by scoria (Healy 1975a). Lakes Okareka, Tikitapu, Rotokakahi, and Rotoma formed as a result of various eruptions between c.19 000 and c.8500 years ago, whereas the main body of Lake Rerewhakaaitu was probably formed only c.700 years ago by damming by pryoclastic flows associated with the Kaharoa eruption from Mt. Tarawera (Table 4; I.A. Nairn pers. comm. 1986).

Lake Rotomahana formed after the 10 June, 1886 Tarawera eruption. This eruption, unusually explosive for basaltic magma (Walker et al. 1984), cored out a 7 km-long chasm crossing Tarawera Mountain (Fig. 6) and extending into the Rotomahana basin, as shown in Plate 3A. Prior to the 4-hour long eruption, which resulted in 153 fatalities, two shallow lakes (Rotomahana and Rotomakariri) occupied the site of the modern lake (Plate 3B), but these were blown out in the phreatomagmatic and hydrothermal explosions that produced the present basin (Nairn 1979; Nairn et al. 1986). The lake took five years to fill and its maximum depth is now 112 m (Appendix B). In the associated Waimangu thermal area to the southwest of Lake Rotomahana, several small lakes (two with hot water) occupy craters produced during and following the 1886 eruption (Healy 1975a; Cole & Nairn 1975; Lloyd 1986).

Plate 2 *View northwest over Mount Tarawera (with rift) in the foreground to the western margin of Haroharo Caldera. Tarawera lavas in the foreground and Haroharo lavas from the right fill most of the caldera (see Fig. 6), and Lakes Tarawera* (front) *and Okataina* (right rear) *occupy the depression between the lavas and the collapsed western margin of the caldera. Lake Okataina was dammed by the near-circular rhyolite lava extrusion (c.7000 years ago) and the adjacent steep lava flow (c.5000 years ago); Lake Tarawera formed when a lava flow (c.5000 years ago) blocked the valley's eastern drainage* (just off the photo to the right). *Lake Okareka* (left rear) *lies in the Okareka Embayment, and in the distance Lake Rotorua occupies part of the Rotorua Caldera (see Table 4).* Photo: D.L. Homer, New Zealand Geological Survey.

Other small circular lakes in the Rotorua area occupy explosion craters. These include Lakes Rotokawau, Rotongata, and Rotoatua, near Lake Rotoiti, and numerous small crater lakes originating from hydrothermal eruptions in the Waiotapu thermal area (e.g., Lakes Okaro and Ngahewa), three of which contain hot water (Lloyd 1959; Cross 1963; McColl & Forsyth 1973; Cole & Nairn 1975) (Table 4).

Taupo area lakes. The lakes in the Taupo area (Appendix A, V1) reflect an extreme contrast in the eruptive styles of the rhyolitic "inverse" Taupo volcano and the andesitic volcanoes of the Tongariro Volcanic Centre (Plate 1; Fig. 8). The flanks of the Taupo volcano, containing Lake Taupo, slope inwards at 1–2° towards the most recent vent locations, steepening in places

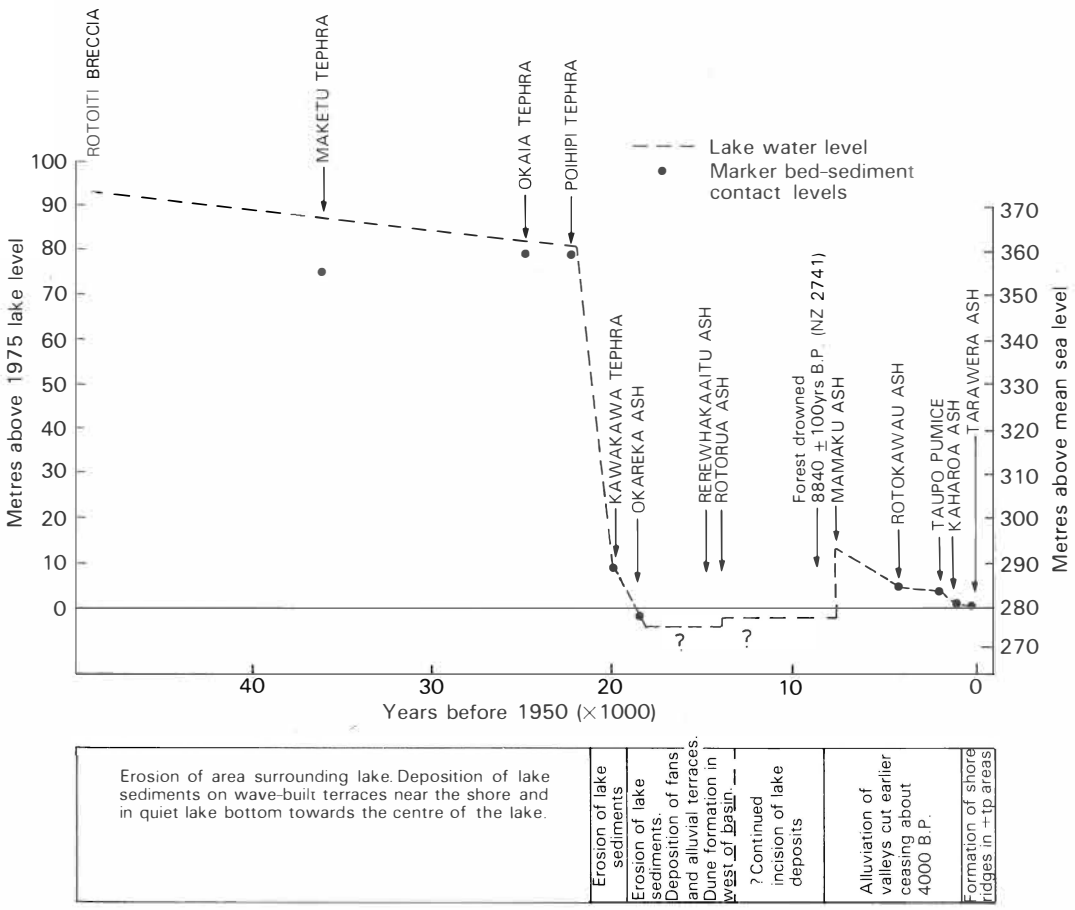


Fig. 7 Inferred variations in the water levels of Lake Rotorua from c.50 000 years ago to the present based on dated tephra marker beds. Present lake level is 280 m a.s.l. (After Kennedy et al. 1978, p.258, and Wood 1986, p.90.)

near the fault-bounded lake margins (Walker 1984). The long and complex history and evolution of Lake Taupo has been discussed by various authors including Grange (1937), Healy (1975a), Froggatt (1982), Timperley (1983), Wilson et al. (1984, 1986), Houghton & Wilson (1986), and Northey (1983, 1986). Based on seismic and other geophysical evidence, the lake may be divided into three structural regions (Fig. 8): the horst-graben complex of the northern bays, the two central calderas (western and eastern), and the graben in southern Lake Taupo (Northey 1986). The Western Caldera is centred in Western Bay and was probably the source of the Whakamaru Ignimbrite (Healy 1982; Northey 1983), although Wilson et al. (1986) have recently suggested an alternative source area to the north of Lake Taupo. The age of this eruption is uncertain, but is likely to have been between c.330 000 and c.350 000 years ago (Briggs 1976; C.S. Nelson, pers.comm. 1986) rather than the recently-published date of c.254 000 years (Froggatt et al. 1986).

Since c.50 000 years ago, explosive eruptions as listed in Table 1 have occurred within eastern Lake Taupo, particularly in the vicinity of the Horomatangi Reefs (Fig. 8; Northey 1983; Cole et al. 1984). The latest eruption from Taupo, known as the Taupo Pumice eruption, oc-

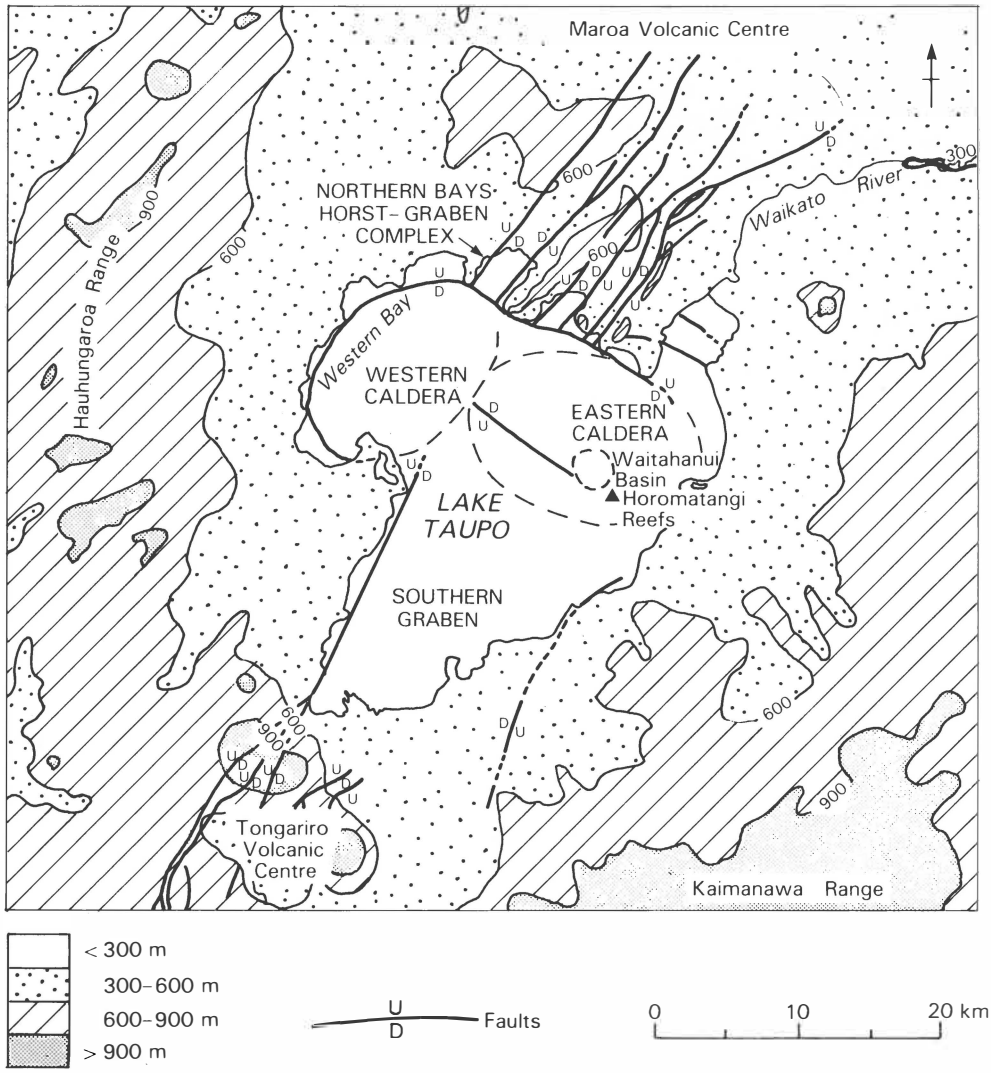


Fig. 8 Broad structure and topography of the Taupo Volcano. Contours in metres. U, upthrown; D, downthrown side of faults. The distribution of these faults imposes the present configuration of Lake Taupo's northern shoreline. Present lake level is 357 m a.s.l. Note: the 300 m elevation contour lies within the lake, close to and approx parallel with the shoreline. (After Wilson & Walker 1985, p.202, and Northey 1983, p.249.)

cured c.1800 years ago in the Horomatangi Reefs area and was the largest eruption for c.20 000 years (Froggatt 1981a; Wilson & Walker 1985). It consisted of several closely-spaced eruptive phases, the last of which was exceptionally powerful and intense, generating an "ultraplinian" eruption column (Taupo Lapilli) possibly 50 km in height and an unwelded ignimbrite (Taupo Ignimbrite) that devastated a roughly circular area c.160 km across (Walker 1980, 1983; Wilson & Walker 1985). The vent location for the ignimbrite phase is marked now by the Waitahanui Basin (Fig. 8; Northey 1983). The specific year of the eruption has been pinpointed as c.A.D. 186, based on ancient Chinese and Roman accounts of unusual atmospheric effects consistent

Plate 3 A *View southwest from summit of Mount Tarawera of the Rotomahana basin soon after its formation during the 10th June 1886 eruption. Present-day Lake Rotomahana is shown in Plate 3B. The photo was taken in late July, or early August, 1886 (probably by F.M.B. Muir or A.H. Burton; R.F. Keam pers. comm., 1986). Photo: Burton Brothers, National Museum of New Zealand, Wellington.*

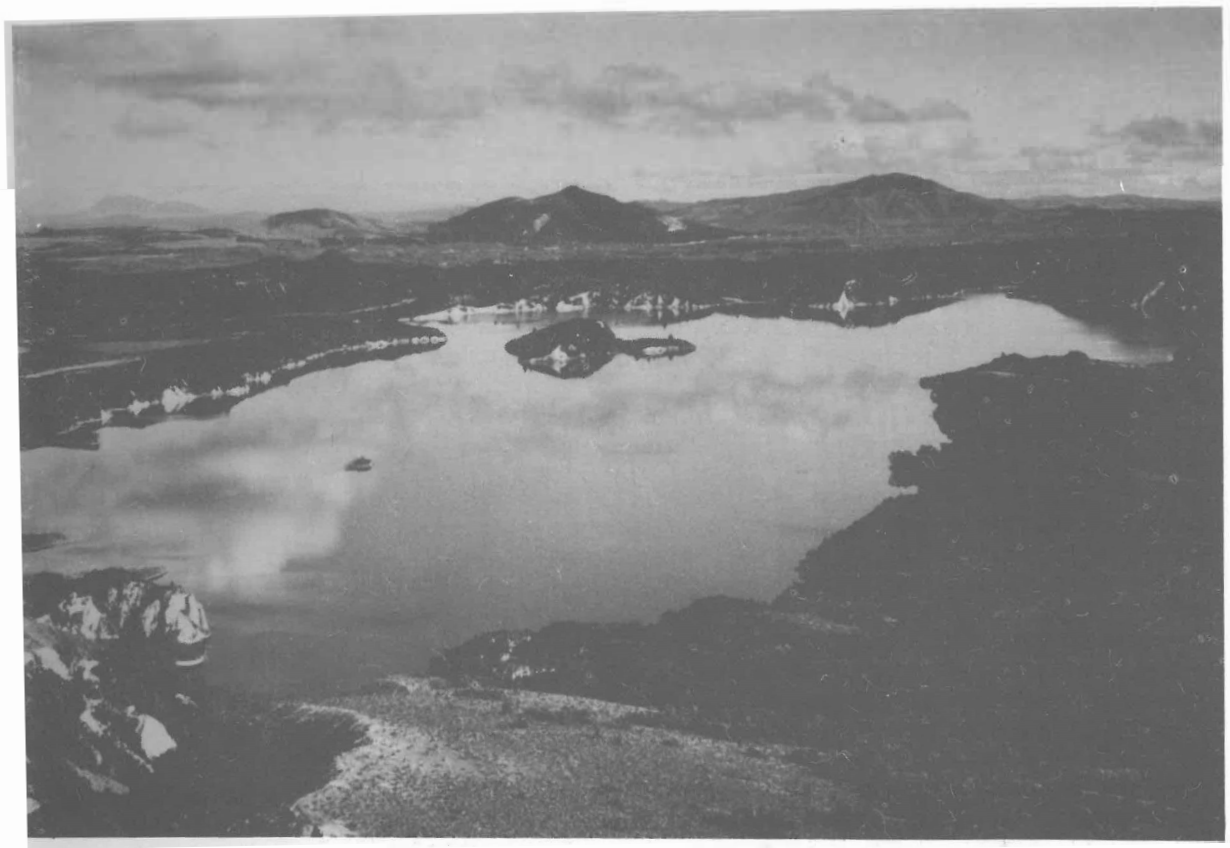


Plate 3 B *Lake Rotomahana at the present day, photographed from a position similar to that for Plate 3A.* Photo: R.M. Briggs.

with the injection of very fine ash (<5 μm) into the upper stratosphere (Wilson et al. 1980), although this interpretation is disputed by Froggatt (1981b).

The Taupo Pumice eruption essentially emptied the lake, as shown by a persistent buried wave-cut bench at 110 m beneath lake level (Northey 1986). The lake refilled in perhaps 10–20 years, rising to c.30 m above its present level until the exit channel (Waikato River) was re-established and the lake fell to its modern level (Grange 1937; Healy 1975a).

Lake Rotongaio, on the eastern shore of Lake Taupo, was considered by Baumgart (1954) and Self & Sparks (1978) to be the source crater of the Rotongaio Ash (a member of the Taupo Pumice Formation). However, Walker (1980) and Froggatt (1981a) discount this conclusion, and the lake is thus unlikely to mark an explosion crater. Instead, it may simply be a barrier-bar lake (Plate 12). North of Lake Taupo, Lake Rotokaua occupies a hydrothermal explosion crater (Cole & Nairn 1975; Table 4).

Lakes Rotoaira, Rotopounama, and Rangatau, together with the crater lakes of Tongariro and Ruapehu volcanoes, occupy basins formed by faulting, damming by lava, and explosion craters (Gregg 1960; Healey 1975a; Cole 1978). Ages of the lakes range from possibly c.10 000 years or more to historical (Table 4).

Lakes in the Auckland and Kaikohe – Bay of Islands districts. These lakes (Appendix A, areas D1, V2) have originated largely through basaltic volcanism. In Auckland, many lakes were formed in craters or dammed against lava flows, but almost all of these have since been drained, commonly through crater wall breaching, leaving diatomite or swampy deposits (Searle 1981). Two examples of lava-dammed lakes are Western Springs and Lake Waiatarua (Table 4). The latter (drained since the 1920s) has been cored for palynological studies and to determine its age of origin. The basal sediments in the core contain basaltic ash, probably derived from Mt. Wellington c.9000 years ago (M.S. McGlone & D.J. Lowe, unpublished). Other lakes in Auckland originated through chiefly phreatomagmatic eruptions that resulted in the formation of explosion craters. Most of these craters have since been inundated by the sea (e.g., Panmure Basin, Tank Farm, and Onepoto), but Lake Pupuke, possibly older than c.40 000 years, remains as a relatively deep (max. depth ≥ 55m) maar (Barker 1970; Searle 1981). It is illustrated in Plate 4.

In Northland, Lakes Omapere and Owhareiti both appear to have originated through damming by lava flows (Bell Clarke 1909; Cotton 1958; Kear 1961). However, – ×C dating of tephra-bearing sediments in cores taken from Lake Omapere (Hogg et al. 1987) has revealed that the modern lake is very young, being formed only c.1000 years ago, but that earlier transitory lakes existed periodically in the Omapere basin. The majority of the discontinuous sediment recorded in the cores is older than c.50 000 years and, from preliminary pollen analysis, appears to represent interstadial or interglacial conditions (M.S. McGlone, pers. comm. 1986). The ealiest lake deposit may hence be as old as c.125 000 years. We suspect that although some of the earlier versions of "Omapere lake" probably formed through lava damming (e.g., by flows from Te Ahuahu volcano), the modern lake possibly originated through siltation of drainage in response to erosion induced by Polynesian deforestation (cf. McGlone 1983b). Skinner (1966) reports that Omapere lake sediments occur up to 12 m above the modern lake level.

Glacial lakes

Lakes of a glacial origin are the most common type of lake in New Zealand (38%; Table 3) and occur exclusively in the South Island (Appendix A, areas G1–G3). Glacial lakes also occur in the Ross Dependency, Antarctica, and on some Sub-Antarctic islands (e.g., Wilson 1967; Priddle & Heywood 1980), and are discussed in chapter 14.

The preponderance of glacial lakes in the South Island, and the distribution of many of them at high altitudes, reflects the extensive glacierisation and reworking of resultant debris in the region during the Pleistocene glaciations as described previously (Fig. 5). Most of the lakes have originated through more than one mechanism, and many have been modified by non-glacial processes such as alluvial aggradation, faulting, landsliding, or coastal processes since their original formation (Suggate 1965; Gage 1975). Usually, such lakes may still be classed as glacial because they occupy basins excavated or modified by ice and dammed by drift (moraine) or glaciofluvial outwash deposits that originated as a direct consequence of the glacial activity. Thus, because of their typically complex origins, Gage (1975) grouped glacial lakes in a deliberately generalised way as follows:

(1) lakes and tarns in ice-excavated rock depressions;
(2) lakes partly or completely enclosed by moraine or associated outwash deposits (includes kettle lakes);
(3) combinations of (1) and (2) with non-glacial factors (e.g., fan-dammed lakes).

Another group, usually temporary but often recurring, is found adjacent to modern glacier ice as ice-margin or proglacial lakes (e.g., Lyell Glacier, Tasman Glacier; see Soons & Gullentops 1973; Gage 1975, 1980).

Plate 4 *Lake Pupuke, a maar in Takapuna, North Shore, Auckland, viewed from the north. The breached Tank Farm* (T) *and Onepoto* (O) *explosion craters, which formerly held lakes, can be seen to the south.* Photo: Whites Aviation, Auckland.

Many small tarns and some larger lakes occupy the hollowed floors of cirques and depressions (e.g., Fig. 9) in the upland areas in northwest Nelson, in the Southern Alps, and in Fiordland. Examples given by Gage (1975, 1980) include Lakes Aorere, Browne, Shirley, Green, Unknown, and Boulder. Hundreds of mountain tarns occur in Fiordland alone (McKellar 1982), including Lake Quill, which occupies a large hanging cirque and overflows as the Sutherland Falls (Cotton 1958; Plate 5).

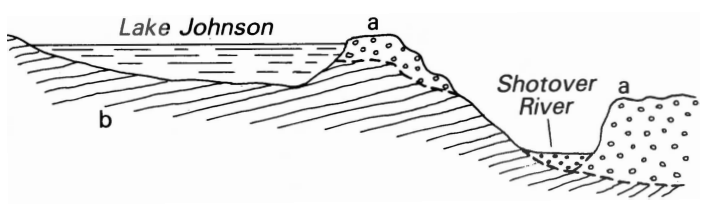


Fig. 9 Sketch of a longitudinal section through Lake Johnson, a glacial rock basin lake at 392 m altitude near Lake Wakatipu. The lake is about 900 m long and has a maximum depth of c.27 m. The rock rim at the lower or outlet end is c.17 m below the summer water level of the lake (after Park 1909, p.19). a = late Pleistocene till (Otiran); b = mica-schist.

Plate 5 *Lake Quill, A glacial cirque-basin lake at 985 m altitude in Fiordland, and the Sutherland Falls (580 m high) cascading into the Arthur Valley. The lake lies in the Franklin Mountains.* Photo: National Publicity Studios, Wellington.

Most of the larger glacial lakes in the South Island occupy overdeepened, formerly ice-filled valleys. Large valley glaciers, some >30 km long, gouged out the troughs now occupied by Lakes Poteriteri, Hauroko, Monowai, and Te Anau in Southland; Wakatipu, Wanaka, Hawea, and Ohau in Otago; Pukaki, Tekapo, and Coleridge in Canterbury; and Rotoroa and Rotoiti (Plate 6) in Nelson. At the same time, the glaciers deepened and shaped the fjords in Fiordland (Bayly and Williams 1973; Pickrill et al. 1981; McKellar 1982). These large glacial lakes thus tend to be steep-sided with flat basin floors (e.g., Fig. 10). The deepest parts of some of them, including Manapouri, Te Anau, and Wakatipu, are below sea level, forming crypto-depressions (Irwin 1972a; see Bathymetry section below and Appendix B).

Although moraines around the ends of some of the large ice-gouged lakes may be only minor features contributing relatively little to the depth of the lakes, few, if any, of the larger glacial lakes are likely to be entirely retained by solid rock (Gage 1975; Soons 1982). Lake Wakatipu (max. depth 380 m; Appendix B) is held mainly by a c.305 m high rock rim which is capped by c.70 m of till (Bayly & Williams 1973). Examples of more or less completely moraine-enclosed lakes are known (e.g., Lakes Brunner, Haupiri, Ianthe, and Mapourika in Westland, and lakes in the Mackenzie Basin), but most glacial lakes are dammed by contemporary alluvial outwash in addition to moraine (Gage 1975, 1980; Irwin 1975a; Soons 1982). Plates 7 and 8 illustrate two such glacial lakes that are dammed by moraine and outwash deposits.

Plate 6 *View from the north of Lake Rotoiti, which occupies a glacially over-deepened valley between the St. Anaud Range* (left) *and the Travers Range and Robert Ridge* (right) *in the Nelson district. The Alpine Fault (see Fig. 1) runs northeast-southwest across the northern end of the lake (arrowed).* Photo: Whites Aviation, Auckland

Some glacial valleys contain small water-table lakes in enclosed hollows within fields of ablation moraine or on undulating moraine surfaces (e.g., Lakes Clearwater, Blackwater, and Alexandrina in Canterbury). These may be difficult to distinguish from kettle lakes, which form in depressions that originate through collapse of deposits by delayed melting of blocks of ice (Gage 1975). Lake Marymere (Fig. 11) is such a kettle lake, and occupies an enclosed depression in the floor of a meltwater channel that was active during a recession of the former Waimakariri Glacier (Gage 1959, 1975). Kettle lakes have recently formed on the riverbed downstream of the receding Fox Glacier when detached masses of stagnant ice buried under gravels slowly melted (Gage 1980).

Lakes impounded partly by alluvial fans or talus fans (screes) are relatively common throughout the South Island mountains. This is because valley sides were over-steepened by the glaciers, becoming unsupported hence commonly unstable after their retreat. While many of these screes are still developing today, especially above the tree line, many were evidently formed and reworked by rivers into alluvial fans soon after final rapid deglaciation c.10 000 years ago (Burrows 1975; Gage 1975; O'Loughlin & Pearce 1982), often to form or modify lakes such as Grasmere, Heron, Poreua, Pearson, and Hawdon (Fig. 11), and Gunn (Plate 9) (Gage 1975).

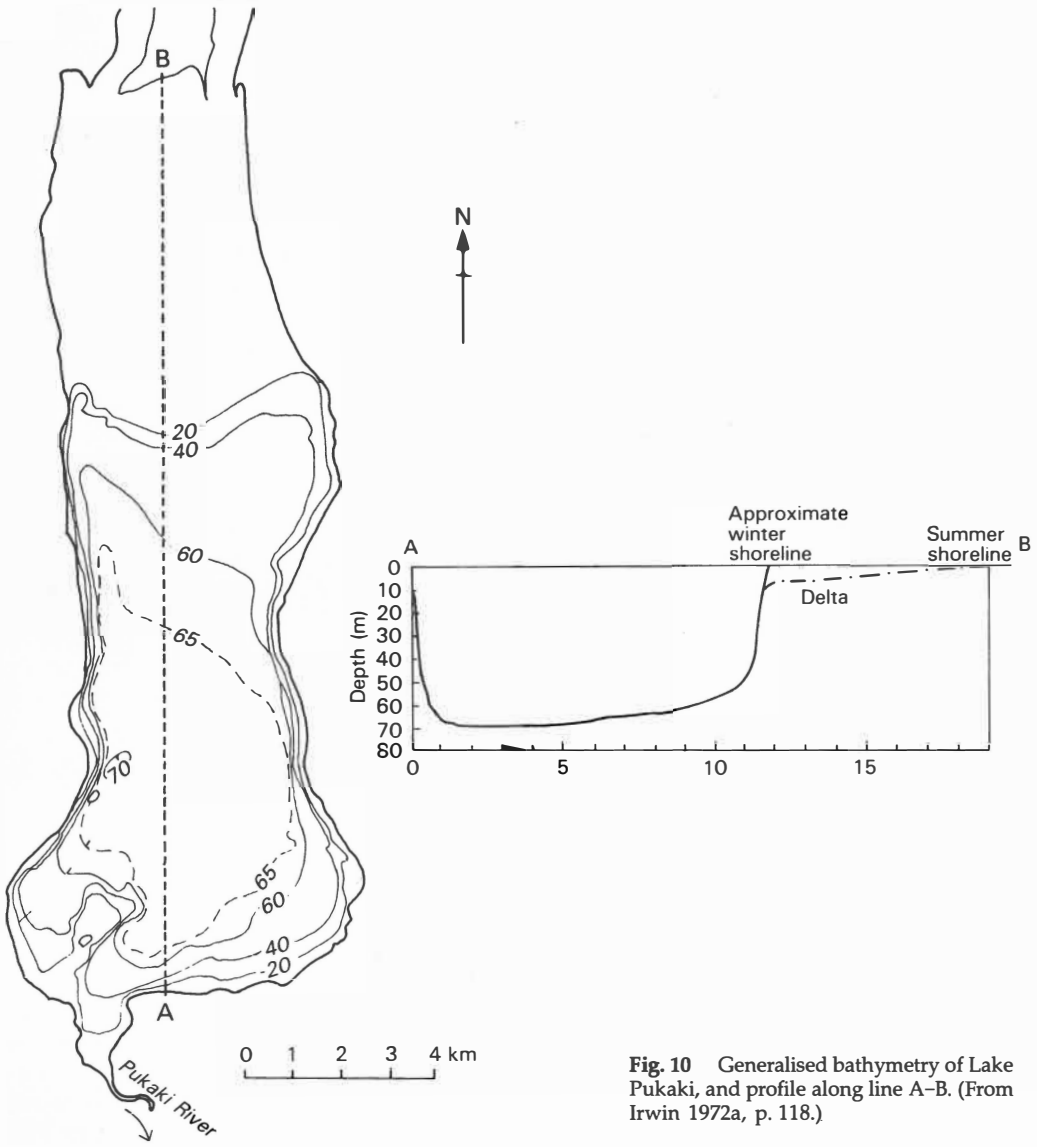


Fig. 10 Generalised bathymetry of Lake Pukaki, and profile along line A–B. (From Irwin 1972a, p. 118.)

Higher lake levels and lake lowering. Nearly all of the larger glacial lakes have stood at higher levels than present, as evidenced by tiers of lake shorelines and associated diatomite above the modern lakes (Plate 8; Gage 1975; Suggate et al. 1978; Wellman 1979). These high level lakes, although probably short-lived, were of considerable lateral extent. For example, a much enlarged Lake Wakatipu was previously contiguous with Lake Hayes (Fig. 12; Park 1909; Brodie & Irwin 1970; Bell 1982). Similarly, Lakes Rotoiti (S.I.), Rotoroa, Tekapo, Pukaki, Ohau, Hawea, and Wanaka have previously been much larger, and probably existed in similar positions during earlier interglacials (Wellman 1979; Fitzharris et al. 1982), as have Lakes Brunner, Te Anau, and Manapouri (Morgan 1911; Gage 1975). Stranded lake beaches and diatomite near Lake Hawdon attest to its previously enlarged existence (Fig. 11; Gage 1959).

Plate 7 *Northward-looking view of Lake Tekapo, Mackenzie Basin, Canterbury. This lake is typical of many of the large glacial lakes. It occupies a formerly ice-filled valley and is dammed chiefly by moraine and contemporary alluvial outwash deposits, seen in the foreground and into which the Tekapo River has entrenched. The Two Thumb Range lies to the east and northeast of the lake.* Photo: Whites Aviation, Auckland.

The shorelines adjacent to the six large lakes shown in Fig. 2A have been progressively tilted since their formation, a result of the different rates of uplift away from the crest of the Southern Alps (Wellman 1979). The tilted shorelines of Lake Tekapo (Plate 7) are plotted in Fig. 2B. The tilting rate is assumed to be constant, hence the approximate ages of the shorelines are proportional to their slope (Wellman 1979). It can be seen from the shorelines that over a relatively short period there was rapid retreat of the "Tekapo Glacier" from the downstream end of the lake, and concomitantly a rapid downcutting of the lake outlet (Fig. 2B). The glacier's retreat is shown by the increase in the length of the shorelines with time. The older and steeper shorelines were restricted by the presence of the glacier at the downstream end of the lake, whereas the younger and flatter shorelines which formed after the glacier had retreated extend for the whole length of the lake. Rapid lowering of lake level by rapid downcutting of the lake outlet is indicated by the shorelines becoming lower without flattening appreciably (Wellman 1979). The sections levelled for the other lakes in the Mackenzie Basin (Pukaki, Ohau, and Wanaka) show a pattern similar to that in Fig. 2B.

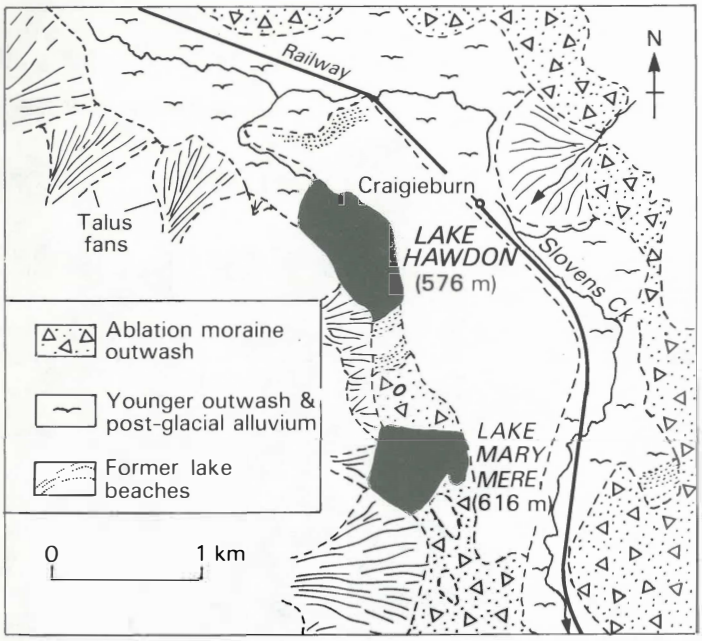


Fig. 11 Lake Hawdon (max. depth 4 m) and Lake Marymere (max. depth 2 m) in the Waimakariri Valley, Canterbury, are both glacial lakes that originated in different ways. Lake Marymere is a kettle lake within an enclosed depression; Lake Hawdon lies in a rock basin partly impounded by postglacial alluvium. (After Gage 1959, p.72.)

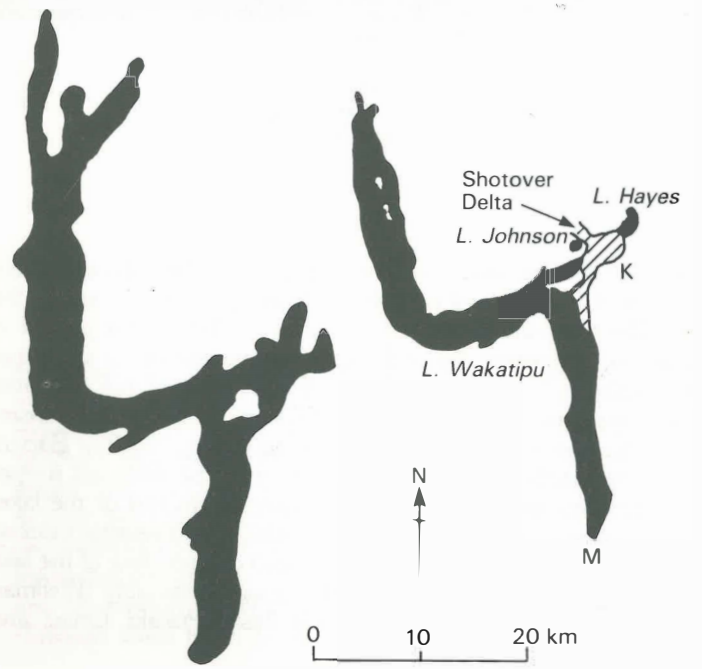


Fig. 12 Sketches of the present - day Lake Wakatipu and Lake Hayes (right) compared with the much larger glacial "Lake Wakatipu" (left) as it probably was following deglaciation after the maximum ice advance of the last glaciation possibly c.26 000 years ago (Bell 1982). An enlarged lake with fluctuating levels reflecting subsequent glacier oscillations may have persisted until shortly after c.10 000 years ago, when, through downcutting of the Mataura outlet (M), the Shotover Delta (hatched) became exposed to isolate Lake Hayes. The Mataura outlet was abandoned in favour of the present outlet, the Kawarau River (K), possibly c.5000 years ago (Bell 1982). (After Park 1909, p.17.)

Plate 8 *Diamond Lake, to the north of Lake Wakatipu in Otago at Paradise, is dammed against the glacierised slopes of Mt. Alfred (right) and between glacial outwash sediments in the Dart (front) and Rees (back) Valleys, These materials were probably deposited soon after the retreat of the enlarged "Wakatipu Clacier" that occupied these valleys. Stranded, higher lake-level shorelines flank the Richardson Mountains on the far side of the Rees Valley.* Photo: National Publicity Studios, Wellington.

Age. Few glacial lakes have been dated directly. Furthermore, an unequivocal chronology of late Quaternary glacial deposits has been difficult to attain largely because of sparse material for ^{14}C dating in moraines in New Zealand and the differing status of individual glaciers in different areas (Burrows 1975; Suggate et al. 1978; Pillans et al. 1982; Soons 1984).

Nevertheless, the correlations that have been achieved suggest that the glacial lakes have existed since deglaciation (Gage 1959). Suggate (1965) suggested that the main glacial lakes in the South Island were all last occupied at about the same time. From relict lake deposits and other evidence noted previously some lakes undoubtedly existed at earlier stages, but it is likely that all glacial lakes in their present form postdate the maximum ice advances associated with the last glaciation (between c.27 000 and 18 000 years ago: Suggate & Moar 1970; Moar & Suggate 1979; Bell 1982; Nelson et al. 1985). Commencement of postglacial environmental conditions can be recognised as early as c.15 000 years ago (e.g., Suggate 1965; Stewart & Neall 1984) but sustained retreat of the glaciers was well underway by c.13 000 years ago, after the last major glacial advance e.g., the Kumara-3 advance of Suggate (1965) between c.13 000-14 500 years ago (Suggate et al. 1978; Burrows 1979; Suggate 1985; Nelson et al. 1985). Pillans et al.

Table 5 Possible ages of some glacial lakes in the South Island (based mainly on correlation of enclosing moraines).*

Lake	Age (years B.P.)	Reference
Heron	≤12 000	Burrows & Russell (1975)
Horseshoe	<13 300	Clayton (1968)
Lady	<14 000	Drake & Burrows (1980)
Letitia	<13 000	Gage (1959)
Grasmere		Suggate et al. (1978)
Sarah		
Pearson		
Lyndon		
Hawdon	13 000 - 17 000?	
Marymere		
Blackwater	<18 500 ?	
Coleridge	<13 000	Suggate et al. (1978)
Sumner	(probably c.10 000–12 000	
Ianthe		
Rotokino		
Wahapo		
Mapourika		
Pukaki		
Tekapo		
Ohau		
Hawea		
Wanaka		
Poteriteri		
Alexandrina		
Wakatipu	c.10 000	Fitzharris et al. (1982)
Hayes	McKellar (1982,	
Johnson	Bell (1982)	
Te Anau		
Manapouri		
Hakapoua		
McKerrow†	c.7700	Pickrill et al. (1981)
Many alpine tarns in Fiordland	<10 000	McKellar (1982)

* Most moraines are correlated with the Kumara-3 advance (Westland) dated at between c.13 000 - 14 500 years B.P. (Suggate 1965; Suggate et al. 1978; Pillans et al. 1982). Soons (1984) has suggested that this advance may have been more recent (c.11 500 - 13 000 years ago).

† This lake is an unusual, tide-influenced fjord lake of glacial origin that was separated from the open sea by a barrier spit (Pickrill et al. 1981).

(1982) have suggested that c.12 000 years ago is perhaps the most appropriate date to mark the beginning of New Zealand postglacial time, although ice still occupied considerable sections of many of the larger valleys in the Southern Alps, hence many of the glacial lakes in more or less their present form must date from near this time (Table 5; see also Soons 1984). Burrows (1979) lists a number of ^{14}C dates on carbonaceous material asssociated with lake sediments from Canterbury and Westland locations of 10 000-12 000 years age. Other lakes formed sub-

Plate 9 *Southward-looking view over Lakes Fergus (foreground) and Gunn in the upper reaches of the Eglinton Valley, Fiordland, the lakes occupy a glacial valley and are partially impounded by alluvial and talus fans, one of which can be seen between the lakes. Small tarns lie on the high ground in the foreground.* Photo: National Publicity Studios, Wellington.

sequently during the glaciers' continued retreat, interrupted by advances of ever-diminishing extent, and the accompanying period of intense erosion and fan building – perhaps until c.9000-10 000 years ago when forests became more widely re-established over most of the South Island (Moar 1971; Burrows 1975, 1979; McGlone & Bathgate 1983). Thus many glacial lakes are likely to be about 10 000 to 12 000 years old, but others may be older (perhaps up to c.15 000 years) or considerably younger, depending mainly on location and mode of formation. Areas where ice retreat was delayed longest (such as in high altitude cirques above c.1000 m) may be expected to contain the youngest lakes.

Lakes formed by landslides

These lakes originate through blockage of drainage in valleys by debris from landslides (Cotton 1958). The active tectonic environment of New Zealand, produces both the rugged terrain needed for the landslides and a major triggering mechanism: earthquakes (Henderson 1937; Adams 1981). Of the eighteen historic landslide-dammed lakes given in Table 6, all but three were the result of earthquakes. A seismic origin for many of the pre-historic lakes seems probable (see

Table 6 Size,* origin, age, and dominant lithology of landslide-dammed lakes in New Zealand. (Mainly after Adams 1981, p.216; some lake areas from Irwin 1975a).

Lake[1]	Area (km²)	Origin of slide[2]	Date of formation[3]	Main rock type of slide
North Island				
Folger	0.2	NE	A.D. 1968	Sedimentary
Ngatapa	2	E	A.D. 1931	Sedimentary
Bruce	<0.1	E	A.D. 1855	Sedimentary
Waikaremoana	55.7	?	≳2200 yr B.P.†	Sedimentary
Rotongaio (area L1)	<0.1	?	ph	Sedimentary
Tutira	1.5	?	ph	Sedimentary
Colenso	<0.1	?	ph	Sedimentary (indurated)
Rotokare[4]	0.09	?	>1920 yr B.P.	Sedimentary
Tiniroto[5]	0.2	?	6500 yr B.P.	Sedimentary (mudstone)
Namunamu	0.17	?	?	Sedimentary
Ngaruru	0.08	?	?	Sedimentary
Te Kapu	<0.1	?	?	Sedimentary
Maungarataiti[6]	<0.1	?	>2620 yr B.P.	Sedimentary
Maungaratanui	<0.1	?	>c.2000 yr B.P.?	Sedimentary
South Island				
Buller	0.6	E	A.D. 1968	Granite
Lindsay, Lower	<0.1	E	A.D. 1929	Sedimentary (indurated)
Stanley	0.6	E	A.D. 1929	Sedimentary (indurated)
Elmer	0.2	E	A.D. 1929	Granite
Moonstone	<0.1	E	A.D. 1929	Sedimentary
Glasseye	0.1	E	A.D. 1929	Sedimentary
Falls	0.2	E	A.D. 1929	Sedimentary
Marina	0.1	E	A.D. 1929	Granite
Perrine	>2	E	A.D. 1929	Sedimentary
Matiri, Upper	0.3	E	A.D. 1929	Sedimentary
Sandstone	<0.1	E	A.D. 1929	Sedimentary
Mud	4.5	E	A.D. 1929	Sedimentary
Thompson	<0.1	E	A.D. 1929	Sedimentary (indurated)
Saddle Hill[7]	<0.1	NE	A.D. 1929	Mudstone
Drysdale		?	A.D. 1913	Sedimentary (indurated)
Matiri	0.6	PE	290-360 yr B.P.	Sedimentary
Chalice	0.5	?	2160 yr B.P.	Schist
Shag	<0.1	PE	ph (? c.A.D. 1650)	Sedimentary
Hanlan	0.1	PE	ph (? c.A.D. 1650)	Sedimentary
Phyllis	<0.1	PE	ph (? c.A.D. 1650)	Granite
Owen	0.2	PE	ph (? c.A.D. 1650)	Granite
Blue Duck	<0.1	PE	ph (? c.A.D. 1650)	Sedimentary
Caslani	<0.1	PE	ph (? c.A.D. 1650)	Sedimentary
Eight Mile	<0.1	PE	ph (? c.A.D. 1650)	Sedimentary
Christabel	3.2	?	? c.1000 yr B.P.	Schist
Minchin	0.1	PE	ph	Sedimentary (indurated)
Kainere	13.3	?	ph	Granite
Lyes	<0.1	?	ph	Schist
Lochnager	3.0	?	ph	Schist
Ada	2.8	? E	ph (? A.D. 1826)	Gneiss
Stump	0.8	? E	ph (? A.D. 1826)	Gneiss
Loch Maree	0.5	? E	ph (? A.D. 1826)	Gneiss

For footnotes to Table 6 see facing page.

Fig. 13), although only the fact of landslide damming is known, not the cause of the landslide. Adams (1981) suggests that the dating of many synchronous landslide-dammed lakes in one area may establish their cause as an earthquake (e.g., Fig. 13), but storms or other non-seismic events may also be possible triggers. High rainfall generally coincides with the areas of fast uplift and high relief (Crozier et al. 1982, p.46), hence in some steepland areas weak sedimentary rocks (Fig. 3), or strongly weathered rock and deep soils, may be subject to high internal water pressure (Crozier et al. 1982).

Despite the high incidence of landslide (mass movement) events in New Zealand, lakes known to have formed by landsliding are uncommon in comparison with many other lake types (Table 3), occurring in catchments comprising mainly sedimentary rocks in eastern North Island (Appendix A, L1), near Wanganui (L2), the northwestern part of the South Island (L3), and in Fiordland (southern part of area G1) (Table 6). This moderately low proportion is partly a result of the overwhelming number of glacial lakes, and partly because of the generally short-lived nature of most landslide lakes. Even large lakes may rapidly infill with sediment eroded from the catchment, or the lakes soon fill with water and the dams wash out (e.g., in the central Southern Alps; Adams 1981; 1985). Consequently, Adams (1981) distinguishes two types of landslide lakes in New Zealand: (1) temporary lakes on large rivers that are soon destroyed; and (2) "permanent" lakes on tributaries that may remain for thousands of years. The permanence of the lakes depends greatly on the size of the landslide and the size of the river dammed. Numerous landslides caused by the 1929 Buller earthquake (Fig. 13) dammed the major rivers in the region, but most of these dams have since been wholly or partially removed. The Mokihinui River, for example, was dammed by a 100 m-wide landslide to form Lake Perrine, which was initially 20 m deep. Some weeks later part of the dam washed out, lowering the lake 8 m. Similarly, a large gravity slide in the Buller earthquake blocked the Matakitaki River to form Mud Lake, a lake that filled in four days, but was later destroyed by a combination of draining and sediment infilling (Adams 1981; Campbell & Johnston 1982). Lake Ngatapa (Te Hoe) was formed during the 1931 Napier earthquake in Hawke's Bay when a landslide dammed a tributary of the Mohaka River. This lake, 2 km long and 25 m deep, appeared to be permanent, but washed out in a flood in 1938 (Adams 1981).

About 70% of the known New Zealand landslide lakes can be considered "permanent" because they either formed in prehistoric times or have an expected life of hundreds of years (Table 6). The largest and most well known "permanent" landslide lake in New Zealand is Lake Waikaremoana (Appendix A, L1). It is dammed by a gravity slide 3 km wide that fell from the south bank of the Waikaretaheke River at least 2200 years ago (Ongley 1932; Pullar & Heine 1971; see Table 6). The lake probably took about ten years to fill with water (Marshall 1926), and has the V-sided and dendritic shape typical of most landslide lakes (Irwin 1975b; Main 1976). Other landslide lakes in the vicinity of Lake Waikaremoana, and in Hawke's Bay and near Wanganui (e.g., Tiniroto, Tutira, Namunamu, Ngaruru, and Maungaratanui), are noted in Table 6 (see Ongley 1932; Fleming 1953; Lillie 1953; Irwin 1975a; Howorth & Ross 1981).

[1] Unnamed lakes named from the river draining them; table excludes some temporary and many small (< 0.1 km^2) lakes formed by the 1929 Buller earthquake and several larger and older lakes for which the evidence of landslide-damming is sparse.

[2] E = from an earthquake; PE = probably from an earthquake; ? E = possibly from an earthquake; ? = uncertain origin; NE = not from an earthquake.

[3] ph = prehistoric; yr B.P. = radiocarbon years before present (old half-life basis).

[4] Age based on ^{14}C date (old T1/2: Wk425, 1920 $\pm$ 110 yr B.P.) on woody lake sediment at 1.2 m depth in core from lake; bottom of lake sediments not seen (Hogget et al. 1987).

[5] Comprises 2 lakes; age from Howorth & Ross (1981).

[6] Age based on ^{14}C date (2620 $\pm$ 90 yr B.P.) on lake sediments in core; bottom of lake sediments not seen (Hogg et al. 1987).

[7] Data from Byars (1960).

* Many are too small to be included in Table 3.

In the South Island, landslide lakes occurring at high altitude in the Southern Alps region may be difficult to distinguish with certainty from the profuse glacial lakes, and some of the landslide lakes described by Adams (1981) and listed in Table 6 were previously categorised by Irwin (1975a) or Gage (1975) as largely glacial or fluvial in origin. Adams' (1981) work thus shows that landslide lakes are probably more frequent than previously estimated, although this had been suspected (e.g., Irwin 1975b). The largest landslide lake in the South Island is Lake Kaniere near Hokitika (Appendix A, G1); other landslide lakes described by Adams (1981) include Lakes Stanley, Matiri, Christabel, and Chalice (Table 6).

Many of New Zealand's landslide lakes have characteristic features that stem from their rapid formation. For example, surfaces of the landslide dams typically comprise large blocks and open crevices, and often contain abundant remains of trees and other vegetation that once grew on the pre-landslide slopes. Standing dead trees when present below lake level may suggest a young age for the lake, and have been used to date the lake's formation in some cases (Table 6).

Lakes in phytogenic basins

Although many lakes have been secondarily affected by peat development, there are few known New Zealand examples of lakes whose basins have resulted primarily from organic accumulations. Hutchinson (1957) notes that such lakes may sometimes form when rapidly growing vegetation impedes drainage, in an analogous manner to the formation of lateral lakes by river levee deposition. Grange et al. (1939) postulated that some of the lakes bordering the peat bogs in the Waikato region may have formed in this way, but this has not been substantiated (Green & Lowe 1985). Peat growth has contributed to lake development at a later stage, however (see next section).

Some small lakes in peat bogs on the Chatham Islands (e.g., Lake Rotokawau) may have formed in hollows in the peat surface resulting from peat fires (Allan 1928; Hay et al. 1970; see also Whitehead 1972).

Ponds and small lakes may also develop on peat surfaces because of differing rates of peat formation in different places, caused by spatial variations in ombrotrophic conditions that result from variations in subsurface relief affecting the supply of soligenous water (Boatman et al. 1981). This process may be operative in New Zealand, and two specific instances are the small lakelets within the Kaipo Lagoon peat bog and other montane bogs near Lakes Waikareiti and Waikaremoana (Appendix A, L1) (Rogers 1984; Lowe & Hogg 1986), and the many pools within the Lagoon Saddle mire near Mt. Bruce, Canterbury (Dobson 1975). In both cases, the pools are <c.10 000 years old; those in the Kaipo Lagoon are possibly c.5000 years old (Rogers 1984; Lowe & Hogg 1986). Lakelets and small pools also occur frequently in the Kopuatai Peat Dome in the Waikato region, and in Ahukawakawa Swamp in Taranaki, and many of these could probably be classed as phytogenic.

Lakes formed by or associated with rivers

Lakes formed in abandoned channels and as a result of levees blocking drainage are widespread on the lower reaches and floodplains of many New Zealand rivers. They are the second most abundant lake type in New Zealand (16%; Table 3), and, apart from Lake Waikare (34 km^2) and Lake Wairarapa (81 km^2), are mostly small (<0.5 km^2) (Table 3).

Oxbow lakes are common in the Kaihu (Appendix A, R1), Manawatu (R5), Taieri (R8), Mataura (R10), Ruamahanga (R6), Wairau (R7), and the lower reaches of the Clutha (D7) river valleys (Cotton 1958). Because they lie on postglacial aggradational surfaces and are probably shortlived (most are close to their parent rivers hence subject to frequent flooding and sediment

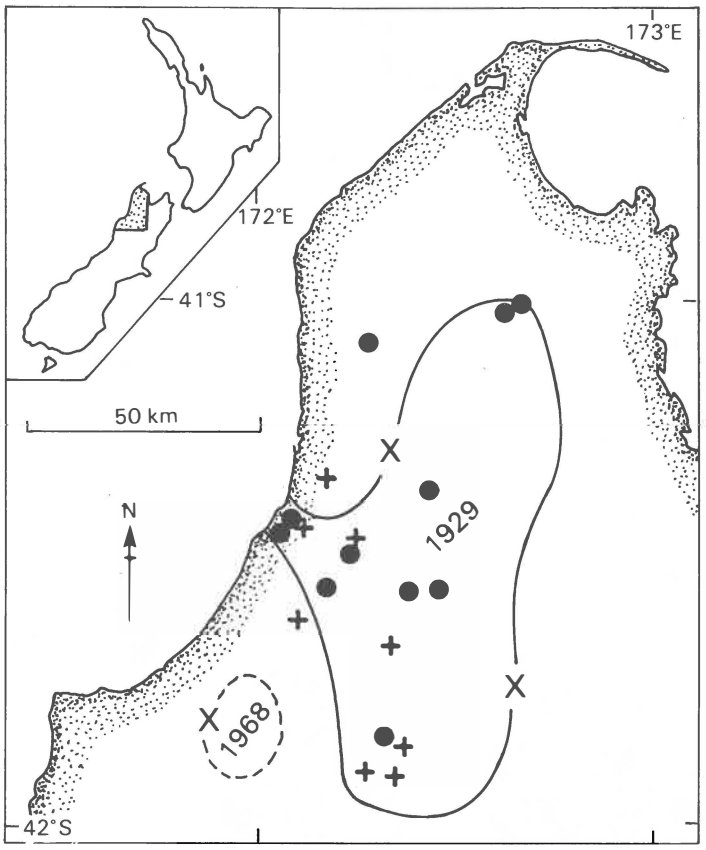
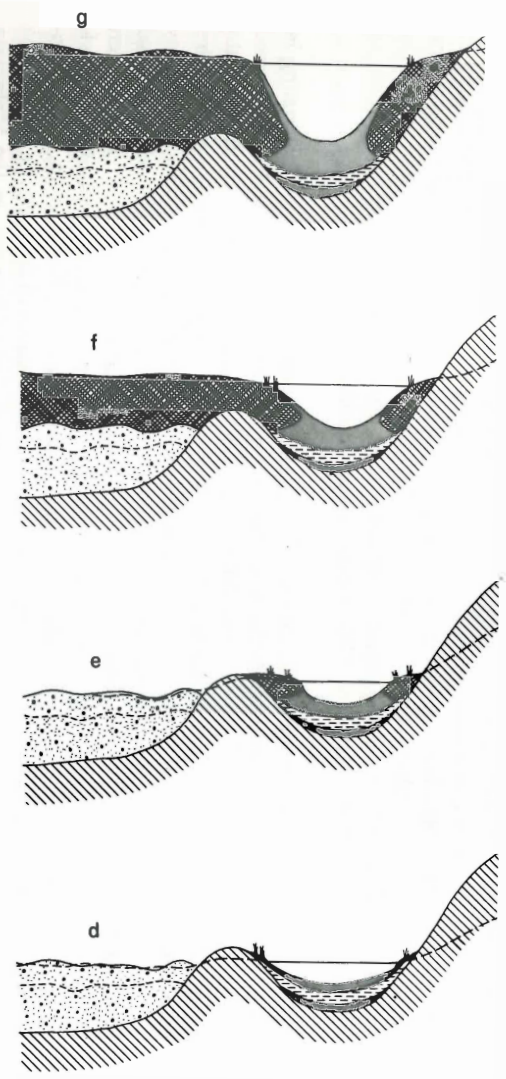
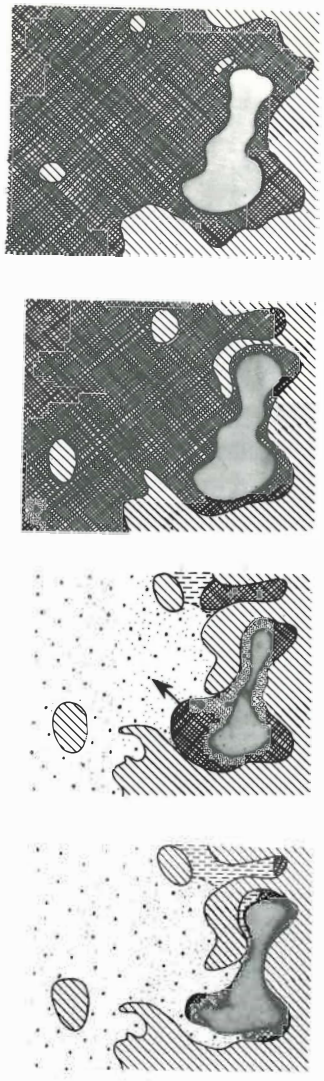


Fig. 13 Map of the north-western part of the South Island showing areas shaken (to Modified Mercalli intensity X) by the 16 June, 1929 Buller earthquake and the 23 May, 1968 Inangahua earthquake (area L3 in Appendix A). Landslide-dammed lakes formed by the 1929 earthquake are shown as dots; similar lakes formed in prehistoric times are shown as crosses. (From Adams 1981, p.217.)

infilling), all these shallow oxbow lakes are likely to be of late Holocene age. Lateral lakes, formed when levees back-up tributary drainage water, are also common. Lake Wairarapa (Appendix A, R6), a large coastal embayment (estuary) until about c.3500-4000 ago (Leach & Anderson 1974; Stevens 1974), was formed chiefly in this manner when the Ruamahanga River built an alluvial dam across the seaward end of the embayment, converting it into a body of fresh water. The progradation possibly followed or was accompanied by regional warping and tilting (Vella 1963; Leach & Anderson 1974). All the lakes in the Waikato valley (Appendix A, R2) are similarly lateral lakes, most being formed as a consequence of the aggradation of the Hinuera Formation (McCraw 1967; Green & Lowe 1985).

The Waikato lakes may be divided into two series of different ages: those originating in association or contemporaneous with the deposition of the Hinuera Formation, and those formed shortly after deposition of Taupo Pumice Alluvium (c.1800 years ago) adjacent to the Waikato River. Most of the lakes in the Hamilton Basin belong to the older series. Radiocarbon dates from sediment cores from many of these lakes, together with tephrochronology (Table 7), show that they formed at much the same time, between c.15 000-17 000 years ago during the final stages of Hinuera-2 sediment deposition in the Hamilton Basin (McGlone et al. 1978; Green & Lowe 1985; Hogg et al. 1987). Several short-spaced episodes of alluvial deposition are evident in the formation of some of the lake basins (e.g., Lakes Maratoto, Rotokaraka, and Rotongata), as shown in Fig. 14. Lake Rotomanuka is possibly older because of the presence of Okareka Ash near the base of a core from this lake alone (Table 7). Lake Okoroire, in the Matamata



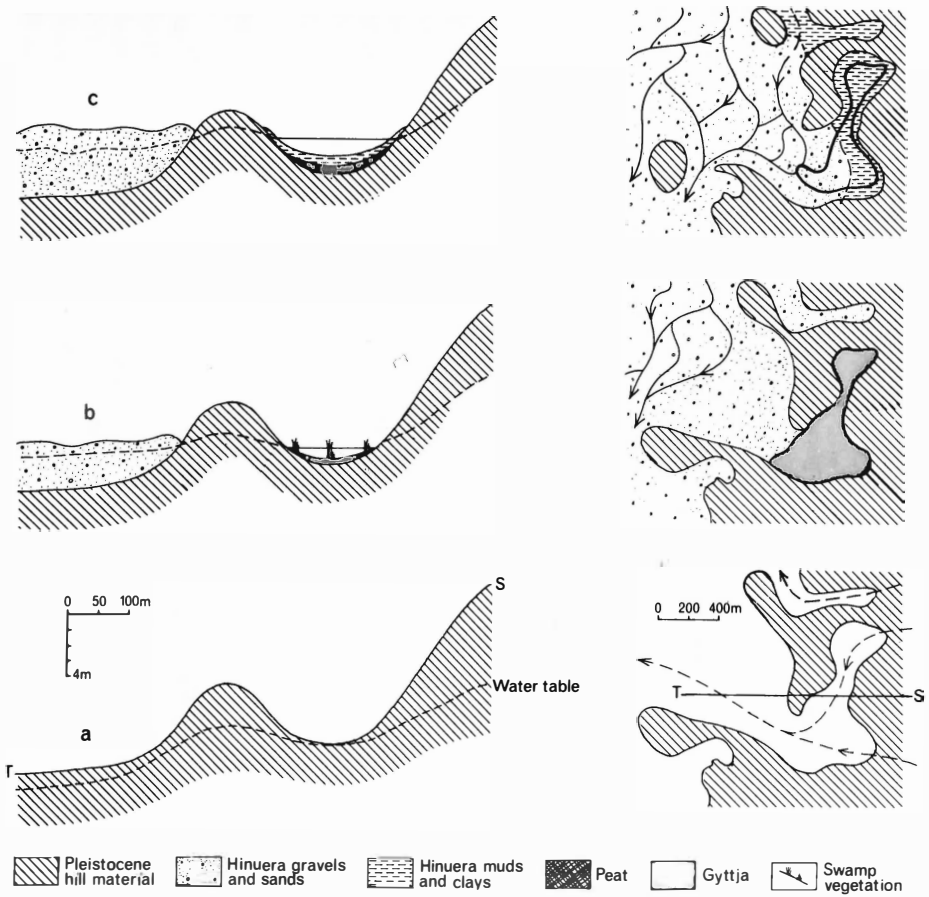


Present day The lake basin is formed in the surrounding peat, perched above and divorced from the initial lake basin in the valley floor. Area and depth of lake at maximum. Other lakes similar to present-day Lake Maratoto, and thus possibly of a similar ontogenetic stage, include Cameron, Pataka, Posa,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

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 the period is Lakes Mangahia, Rotoroa (Hamilton), 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. Gyttja olive-grey, low in organic matter. Gyttja darkens later in 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.



16 300 years ago Second phase of Hinuera-2 deposition in the area. Coarse alluvial sediment deposited in valley mouth, fining to muds and clays at the end of the valley. Lake Maratoto forms, c.2 m deep. 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 Summary of the mode of formation and subsequent developmental history of Lake Maratoto (heavy outline). Cross-sections have a vertical exaggeration of x25. Possible modern analogues (other Waikato riverine lakes) of the major developmental stages are given also. (From Green & Lowe 1985, pp.694-695.)

Table 7 Radiocarbon dates on lake sediments and other material, obtained from sediment coring, which date the initial formation of some Waikato riverine lakes. Some lakes have been indirectly dated using tephrochronology and sedimentation rates (data from Lowe et al. 1980; McGlone et al. 1984b; Green & Lowe 1985; Lowe 1986a; Hogg et al. 1987 (see text).

Lake	Age (years B.P.)*	Stratigraphic position of sample/ Basis of age interpretation	Material†
		Series 2 lakes	
Hakanoa	2040 ± 50	Underlies Taupo Pumice Alluvium (TPA) on pre-lake terrestrial muds	W
Waahi	c.1800	Lake sediments overlie TPA on pre-lake terrestrial muds and pests	-
Ohinewai	c.1800 and >c.4000	Lake sediments overlie TPA, which overlies older tephra-bearing lake sediments (base of lake sediments not seen)	-
		Series 1 lakes	
Maratoto	15 850 ±130 16 300 ± 250	Base of lake sediment overlying alluvial mud of HF‡ (last	G G depositional episode)
	16 900 ± 470 16 200 +360 −340	Top of proto-lake sediment underlying HF muds (last depositional episode)	G G
	17 050 ± 200	Base of proto-lake sediments overlying pre-lake colluvium	G
Kainui (= Lake D)	15 150 +680 −630	Base of lake sediment overlying sandy mud of HF	G
Tunawhakapeka (drained Rototuna lake)	17 600 ± 190	Peaty base of lake sediment overlying sandy mud of HF	WP
Leeson's Pond	>15 700 ±200	Bottom of core (base of lake sediment not seen)	G
Rotokaraka	13 800 ± 370	Base of lake sediment overlying HF mud (last depositional episode)	G
	15 900 ± 630	Proto-lake sediment between last and 2nd-last depositional episodes of HF	G
	16 600 ± 260	Proto-lake sediment between 2nd-last and 3rd-last depositional episode of HF	G
Rotomanuka	>c.17 000	Presence of Okareka Ash¶ in lake sediments at bottom of core (base of lake sediment not seen)	-
Okoroire	>15 850 ± 320	Bottom of core (base of lake sediment not seen)	G
Waikare	17 800 ± 200	Within lake sediments c.1.5 m above base of lake sediments overlying sand of Karapiro or Puketoka Formation	P
Rotongata	c.16 000	Presence of Rerewhakaaitu Ash¶ within lake sediments that overlie HF muds	-

Table 7 continued

Lake	Age (years B.P.)*	Stratigraphic position of sample/ Basis of age interpretation	Material†
Ngaroto	c.16 000	Presence of Rerewhakaaitu Ash within lake sediments that overlie HF muds	-
Mangakaware	c.16 000	Presence of Rerewhakaaitu Ash within lake sediments that overlie HF muds	-
Hamilton (Rotoroa)	c.16 000	Presence of Rerewhakaaitu Ash within lake sediments that overlie HF muds	-
Rotokauri	>c.13 300	Presence of Rotorua Ash¶ at bottom of core (base of lake sediments not seen)	-
Mangahia	>c.15 000	Presence of Rerewhakaaitu Ash within lake sediments (base of lake sediment not seen)	-

* Note that dates are reported here and in the text on an old half-life (Libby) basis (Hogg et al. 1987).
† W = wood; WP = woody peat; G = gyttja or dy-gyttja; P = peat.
‡HF = Hinuera Formation.
¶ Tephra ages given in Table 1.

Basin (Lowe 1986a), may be as old as c.24 000 years on the basis of it being formed by an earlier depositional episode of Hinuera Formation (between c.19 000-24 000 years ago; Cuthbertson 1981). Lake Ohinewai, near Huntly, is a "two-storeyed" lake; the present lake is formed within Taupo Pumice Alluvium, but overlies lake sediments deposited in an older Hinuera-dammed lake (Table 7).

Subsequent development of many of the lakes in the Hamilton Basin (e.g., Maratoto, Cameron, Pataka, Posa, and Mangahia) has been affected by the growth of large, c.10 m-deep ombrogenous peat bogs which formed on the Hinuera Surface probably in response to increasing rainfall c.10 000-12 000 years ago (Green & Lowe 1985). Studies on Lake Maratoto show that this lake, and others like it, was not obliterated by the peat growth around it as one might expect, but increased in area from c.13 000 years ago to the present, probably because either drainage water from adjacent hills promoted microbial breakdown of encroaching peat, or because of erosion of peat at the lake margins by wave action, or both (Fig. 14). Other lakes have not been directly affected by the growth of the peat bogs, although all of these are affected to varying extents by local swamp development around their margins (e.g., Lakes Rotomanuka, Ngaroto, Mangakaware, and Rotokauri; Plate 10). This marginal swamp development is common in many riverine lakes in New Zealand (Irwin 1975a).

Wind-blown dune lakes

Sand dune lakes, the third most common lake type in New Zealand (15%, Table 3), originate by the blocking of valleys or depressions by wind-bown sand deposits. Such deposits are abundant on the west coast of the North Island, hence most dune lakes occur there (Appendix A, W1, W2). Others are found on the east coast of the North Island, at a few locations in the South Island (Appendix A, W3, W4), and on the Chatham Islands (e.g., Lake Pateriki, Hay et al. 1970).

Plate 10 *View looking southeast over Lake Rotokauri, a riverine lake in the Waikato region near Hamilton. The lake was formed, probably c.16 000 years ago, when alluvium was deposited across the mouth of a horseshoe-shaped valley (right midground, marked by the rows of poplar trees) by the ancestral Waikato River. The lake is thus enclosed mainly by the low hills seen in the background and extending round to the middle foreground, and the alluvial dam. There has been local peat development around the lake's margins. (See also Fig.14.)* Photo: J.D McCraw.

The sand dune systems of the west coast of the North Island occur in coastal strips up to about 50 km wide that comprise belts of dunes typically subparallel to the present coastline (e.g., Fig. 15). The belts progressively increase in age inland from unstable active frontal dunes on the coast, formed in only the last 150 years or so, to moderately weathered, stable dunes of early Pleistocene (or possibly Pliocene) age that rise to elevations of 100 to 200 m (Schofield 1970; Chapell 1975; Barter 1976; Richardson 1985). The mechanisms and controls of dune progradation are complex and controversial (Healy & Kirk 1982), but the formation of the dune belts largely in late Holocene times appears to be roughly synchronous along the west coast of the North Island and probably elsewhere in New Zealand (Fleming 1953; Cowie 1963; Pain 1976, 1979; McLean 1978; Heerdegen 1982; Palmer 1984; McFadgen 1985). Many dune lakes, often together with peat swamps, occur at boundaries between the dune belts as shown in Fig. 15, enabling their minimum ages to be estimated from the ages of the dunes forming the dams. Most lakes are probably less than c.5000 years old (Table 8). An exception is in the Kawhia-Aotea Harbour area where the lakes (e.g., Lake Taharoa) appear to be older than c.50 000 years (Table 8).

The presence of these older lakes suggests that lakes have probably always been associated with the dune deposits on the New Zealand coastline, but, because of the dynamic nature of the coast and fluctuating sea levels, have been drained or infilled by successions of later deposits. Some of the modern Holocene lakes may therefore overlie older lake deposits.

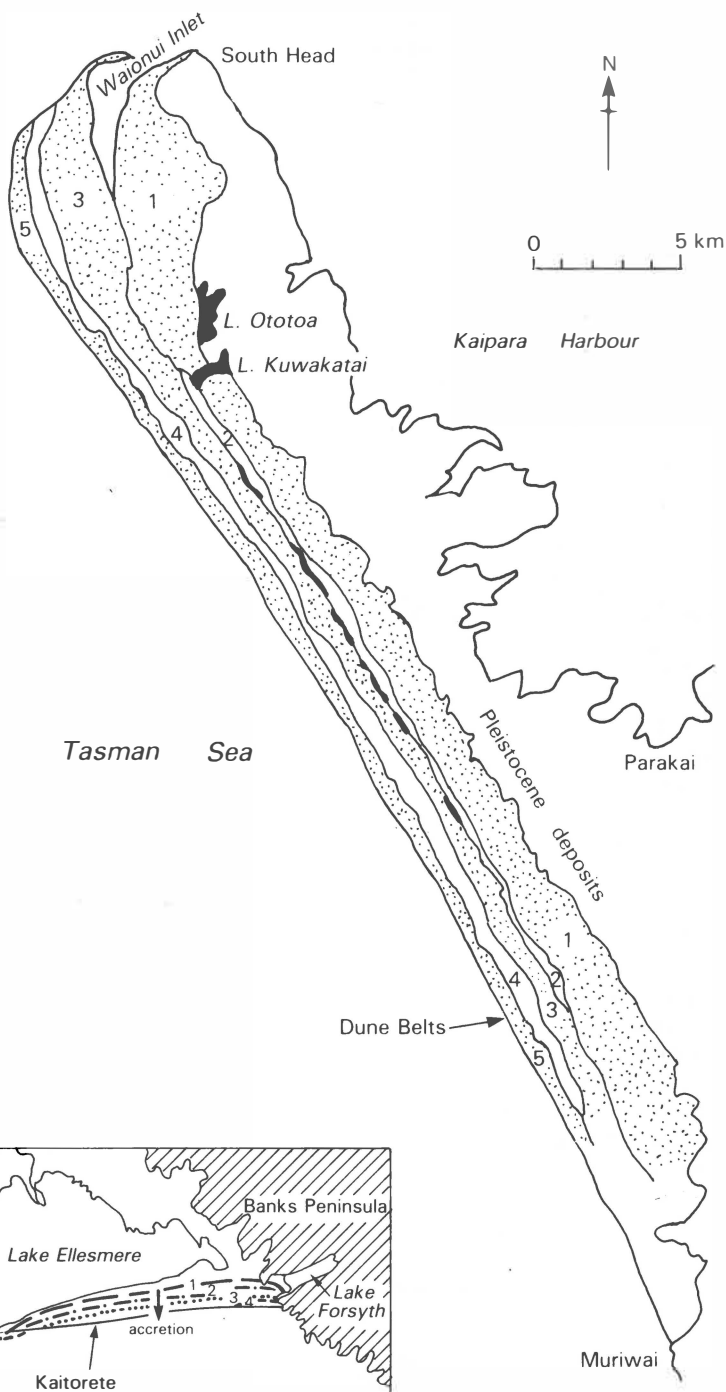


Fig. 15 Holocene dune belts and the alignment of lakes (black) along their contacts on South Kaipara Peninsula, North Island. According to Schofield (1975) the dune belts represent periods of progradation associated with a postglacial sea level fall (with fluctuations): **1** = c.4500 - 3000 years ago; **2** = c.3000 - 2000 years ago; **3** = c.2000 - 1500 years ago; **4** = c.1500 - 300 years ago; **5** = c.300 years - present. (After Schofield 1975, p.297.)

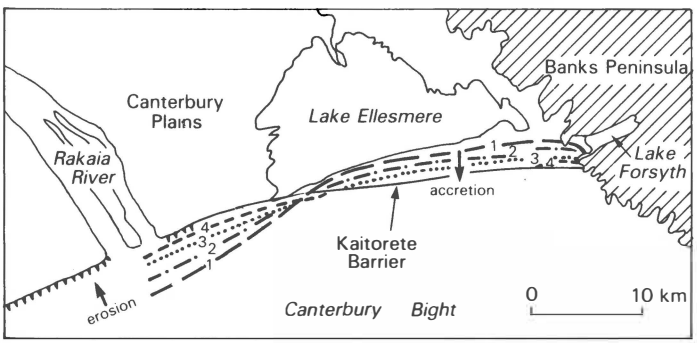


Fig. 16 Kaitorete gravel barrier impounding Lakes Ellesmere and Forsyth, and its reorientation from erosion and accretion since c.6000 - 7000 years ago. Lake Ellesmere was originally larger than present (Armon 1974). Lake Forsyth has apparently been permanently impounded since early European settlement (by barrier 4), previously being open to the sea (Speight 1930). If barriers 1-3 previously extended right across the inlet of the basin, the lake may have existed earlier (until the barriers were breached). (After Armon 1974, p.71, and McLean 1978.)

Table 8 Estimated minimum ages of some dune lakes on the west coast of North Island.

Lakes	Age (years B.P. or period)	Basis of estimate	References*
		North Kaipara Peninsula	1, 2
Karaka Mokeno Humuhumu Kanono Kahuparere	Late Holocene	Dammed by shifting dune sand	
Shag Waikere Taharoa Kai-iwi	Mid Holocene	Dammed by fixed dune sand	
		South Kaipara Peninsula	3 (see also Fig. 15)
Kereta Karaka Pouta Ngakaru Piripoua	1500 - 2000	Dammed by Dune Belt 3	
Kuwakatai	2000 - 3000	Dammed by Dune Belt 2	
Ototoa	3000 - 4500	Dammed by Dune Belt 1	
		Awhitu Peninsula	4
Pokorua Whatihua Rotoiti Otamatearoa Pehiakura	Mid-Holocene or younger	Dammed by Dune II	
		Kawhia-Aotea Harbours	5
Parangi Taharoa Nukumiti	c.50 000 - c.83 000	Dammed by Te Akeake Sands (formed before deposition of Rotoehu Ash dated c.50 000 yr B.P.)	
Rotoroa Rototapu Harihari			
		Manawatu-Horowhenua	6, 7, 8, 9
Waipu Koitiata Heaton Pukepuke Kaikokopu Koputara	350 - 550	Dammed by Waitarere Sand Phase (earlier)	
Alice Omanuka	600 - 1800	Dammed by Motuiti Sand Phase	
Horowhenua Papaitonga	2000 - 5000	Dammed by Foxton Sand Phase	

* 1 = Thompson 1961; 2 = Richardson 1985; 3 = Schofield 1975; 4 = Barter 1976; 5 = Pain 1976; 6 = Cowie 1963; 7 = Heerdegen 1982; 8 = McFadgen 1985; 9 = Shepherd 1985.

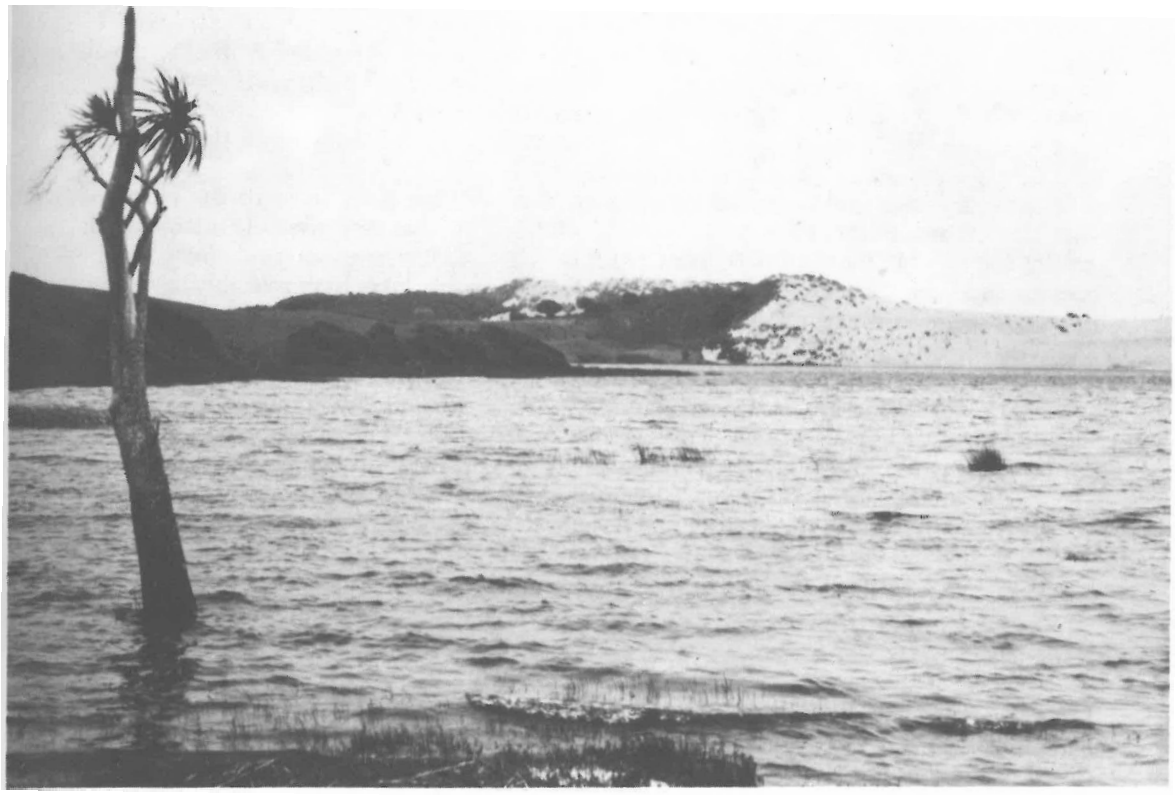


Plate 11 *Lake Humuhumu, a wind-formed lake on North Head, Kaipara Harbour, Northland. The lake has been formed between recent active dunes advancing from the west (background) and older, consolidated dunes, seen to the left.* Photo: M.A. Chapman

The sand dune lakes may be grouped into basin or valley lakes according to their mode of formation. Basin lakes occur in depressions in consolidated dunes (e.g., Lakes Waingata, Rotokawau, and Brewers), or between consolidated dunes and shifting dunes (e.g., Lakes Kanono, Kereta, Horowhenua, and Humuhumu: Plate 11). Valley lakes occur where streams draining consolidated dune sands or other materials are blocked by younger dune sands (Ferrar 1934; Fleming 1953; Cunningham et al. 1953; Brothers 1954). The latter group may vary considerably in shape and often consist of two or more long narrow arms (e.g., Lakes Ototoa and Kuwakatai; Fig. 15), or are sub-triangular in shape (e.g., Lakes Swan and Heaton) (Cunningham et al. 1953; Bayly & Williams 1973). Some dune lakes (e.g., Waikare, Taharoa, and Kaiiwi) evidently have a complex origin (Irwin 1972a), and many have neither inlet nor outlet streams (Cunningham et al. 1953; Cassie & Freeman 1980).

Barrier-bar lakes

These lakes are relatively uncommon and form by the enclosure of inlets or embayments by barrier-bars or spits. The barriers form through wave action coupled with tectonic movements and sea-level fluctuations (Cotton 1958; Wellman 1967; Stevens 1974) and usually lie adjacent to river mouths close to the sea as shallow lagoons (Irwin 1975a). In the North Island they

occur along the Wellington-Palliser Bay coastline and near the Wairoa River mouth near Gisborne (Appendix A, B1, B2). In the South Island, barrier-bar lakes are found mainly on the east coast and include Lakes Grassmere, Ellesmere, and Forsyth (Appendix A, B3-B5). Small lagoonal lakes occur in Westland (e.g., Lake Windemere), on Ruapuke Island in Foveaux Strait, and on Chatham Island (e.g. by Te Whanga Lagoon, Hay et al. 1970). A few barrier-bar lakes are found associated with inland lakes, e.g., Onewhero Lagoon by Lake Rotoma, (Irwin 1975b), and Lake Rotongaio by Lake Taupo (Plate 12).

All the coastal barrier-bar lakes, typically D-shaped, are likely to be of late Holocene age. The few studies that have been done (Table 9) indicate that they generally attained their present form within the last c.6500 years when the postglacial transgression culminated at the present sea level in New Zealand (Gibb 1983). Most barrier-bar lakes have probably developed in several stages involving spit growth and shoreline reorientation by erosion and accretion as illustrated for Lake Ellesmere in Fig. 16 (see also Stevens 1973; Armon 1974; Mildenhall & Moore 1983). The date of transition from essentially estuarine to lacustrine conditions after barrier development is usually uncertain, even with good ^{14}C dates, because of assumptions about uplift rates and small sea level fluctuations (e.g., Leach & Anderson 1974; Palmer 1984). Coastal barrier-bar lakes today are commonly brackish because of easy access to the sea (e.g., Lakes Onoke, Grassmere, and Ellesmere). Some may remain land-locked until they fill to certain levels when channels are cut through the barriers and waters drain out to sea (e.g., Te Whanga Lagoon on Chatham Island breaches naturally in approximately 7-year cycles, Hay et al. 1970), although levels may be controlled artificially (Hughes et al. 1974; Palmer 1984).

Karst lakes

Lakes associated with karst landscapes (or solution lakes of Hutchinson 1957 and Bayly & Williams 1973) are rare in New Zealand. Normally such lakes (e.g.) Lake Koraha) occur in enclosed depressions (e.g., poljes and dolines, or sinkholes) and are typically temporary (Cotton 1958; Irwin 1975a). The largest known example in New Zealand is Lake Disappear (Plate 13), which periodically occupies a polje associated with Tertiary carbonate rocks in the Waitomo area near Aotea Harbour (Appendix A, K1). The polje is inundated after wet weather when

Table 9 Possible ages of initial development of some barrier-bar lakes.

Lake	Age of formation (yrs B.P.)	Reference
Onoke	c.4000 - 5500	Stevens 1974
Kohangapiripiri Kohangatera	c.3100	Stevens 1973, 1974
Pounui	c.2200 - 4000	Palmer 1984
Grassmere	< 10 000	Campbell & Johnson 1982
Ellesmere*	c.6000 - 7000	Armon 1974; Healy & Kirk 1982
Forsyth	c.150 - ?1000	Speight 1930; Gage 1980
Rotongaio	c.1800	

* See also Fig. 16

Plate 12 *Lake Rotongaio, a barrier-bar lake on the east side of Lake Taupo. Currents in Lake Taupo are commonly northwards and parallel to the shore (bottom right to top left).* Photo: M.M. Gibbs.

the flood inflow is greater than the streamsinks can discharge (Williams 1982). Henderson & Grange (1926) report that the lake attains depths of c.15 m after filling. Other small doline lakes occur in the limestone country around Lake Disappear (Irwin 1975a).

Small, perhaps periodic, karst lakes probably occur in limestone and marble terrains in the Hawke's Bay, Wairarapa, Nelson, and South Canterbury regions (Bayly & Williams 1973; Campbell & Johnston 1982). Lakes Marakapia and Rotoparaoa on Chatham Island probably formed initially as doline lakes but have been subsequently modified by sand dune barriers (Allan 1928; Hay et al. 1970).

Man-made lakes

Most of these lakes have been made this century, many since the 1950s (Department of Statistics 1985). In general, large artificially dammed lakes provide storage for hydro-electric power generation, and small artificially dammed lakes, including farm ponds, are reservoirs for urban and rural water supplies or irrigation systems. Future artificial lakes will also include those formed when worked-out open-cast mines are flooded (e.g. in the Huntly area near Hamilton).

The major North Island hydro-electric lakes are found on the Waikato River, draining Lake Taupo (Appendix A, D2) (Hall 1975); in the South Island, most occur on the Waitaki (D6) and Clutha (D7) river systems (Ministry of Works 1967; Department of Statistics 1985). Lake Benmore, on the upper Waitaki River, was formed in 1965 and is New Zealand's largest artificially dammed lake (Appendix B). The nearby Lake Ruataniwha on the Ohau River was filled in 1982. Lake Rotorangi, an earthdam-impounded lake on the Patea River near Wanganui, was filled in 1984 and is the youngest and the longest (46 km) artificially dammed lake in New Zealand.

SEDIMENTATION

Most studies on sedimentation in New Zealand lakes have been done on glacial lakes and artificially-dammed lakes (reservoirs) predominantly with headwater inflows (e.g., Pickrill & Irwin 1980; Phillips & Nelson 1981; Pickrill & Irwin 1982, 1983). By contrast, there have been few studies on the lakes with insignificant inflows such as many of the volcanic and wind-formed lakes in the North Island, an exception being Nelson's (1983) study on Lake Rotoma. Unpublished studies have been made on Lakes Taupo (Lister 1978; Warner 1985), Rotoiti (Craig 1985), and Waahi (Schicker et al. 1986).

Processes of sedimentation

In those New Zealand lakes in which water and sediment inputs are dominated by river inflows, sedimentation usually follows the pattern found by Phillips & Nelson (1981) in Lake Matahina. They presented a depositional model for the lake which incorporated four interdependent but distinct mechanisms: delta progradation, sediment density surges, river plume dispersion, and pelagic settling (Fig. 17).

Delta progradation due to reduction in water velocity at the confluence of river and lake is the deposition of fluvial bedload sediment on the delta platform and upper delta face. The size of the delta and rate of delta progradation depend on the rate of river inflow and the sediment load. In large glacial lakes, rates of delta progradation have generally not been determined but very large deltas have built up in many of them (e.g., see Fig. 10; Wakatipu, Brodie & Irwin 1970, Pickrill & Irwin 1982; Tekapo, Irwin 1978, Pickrill & Irwin 1983; Pukaki or Ohau, Irwin 1972b, 1978; Irwin & Pickrill 1983; Wanaka, Irwin 1980; McKerrow, Pickrill et al. 1981), because of the large supply of glacially eroded sediment and high river flows, especially during spring and summer (Brodie & Irwin 1970). In Lake Matahina maximum inflows are in June and October and rates of delta progradation 35-40 m $year^{-1}$ (Fig. 17; Phillips & Nelson 1981). The outer face of the Ohau River delta in the artificially dammed Lake Benmore prograded at an accelerated rate of c.200 m $year^{-1}$ between 1979 and 1982 when outflow from the adjacent Pukaki and Tekapo Rivers was diverted into the Ohau River (Pickrill & Irwin 1986). In contrast, the low flows in the Pukaki and Tekapo Rivers resulted in negligible deposition on these deltas. Rapid delta progradation can sometimes severely limit storage capacity in small water supply reservoirs. In Morton Reservoir, Wellington (Pickrill & Irwin 1980), the Georges Creek delta has infilled much of the Georges Creek basin. In 40 years the delta face advanced 85 m, with a maximum fill of 3-4 m just off the delta face. Detailed studies of the sedimentation on the Ruamahanga River delta in Lake Wairarapa, where a multiple series of sublimnic sand bars has developed around its outer edge, have been made by Pickrill & Irwin (1978). In Lake Taupo, the most important input of sedimentation has occurred on the prograding Tongariro River delta (Lister 1978), and this area has recently been studied in detail by Warner (1985).

Sediment density surges are intermittent events caused by slumping of deltaic deposits to form high density turbulent flows. In Lake Wakatipu, density surges are known to have been caused by earthquakes (Brodie & Irwin 1970), and this triggering mechanism may also apply in Lakes Tekapo and McKerrow (Pickrill et al. 1981; Pickrill & Irwin 1983). They may additionally be caused by sediment overloading, delta-edge wave action, and sudden flooding of the surface and leading edge of the deltas after periods of low lake levels (Phillips & Nelson 1981). Such slumping may transport large volumes of sediment and affect large areas of the lake floor. For example, in Lake Tekapo rotational slumping on the Godley River delta may incorporate up to 8.25×10^6 m^3 of sediment in a single event, sediment volumes equivalent to several times the total sediment budget, redistributing sediments that have been deposited

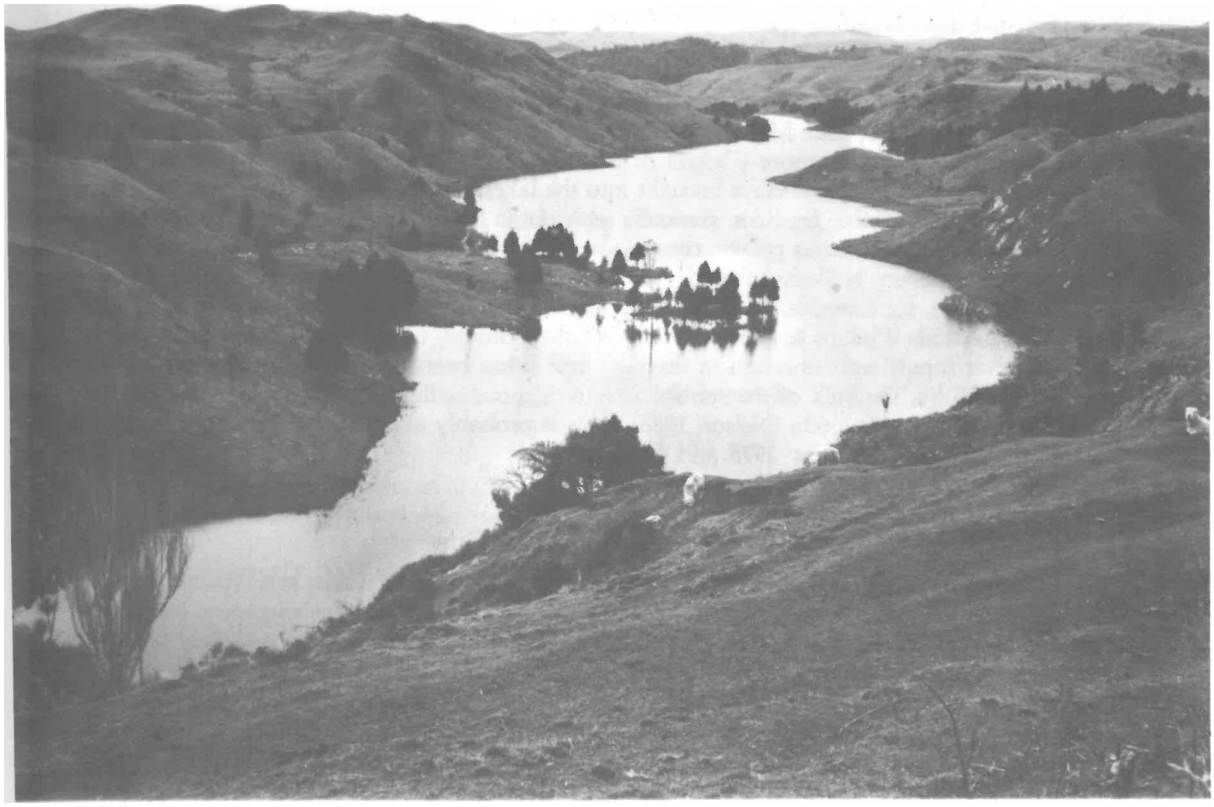


Plate 13 *Lake Disappear, a karst lake north-east of Aotea Harbour, northern King Country, occupies a large enclosed depression (polje) periodically inundated when the flood inflow is greater than the streamsinks can discharge.* Photo: P.W. Williams.

during the preceding 200-600 years (Pickrill & Irwin 1983). Catastrophic density surges have been invoked to explain the sand lenses in cores taken well away from deltaic areas (e.g., Lake Matahina, Phillips & Nelson 1981). In Lake Wakatipu, density surges capable of transporting sediment coarser than mud down the length of the lake are thought to be infrequent (Brodie & Irwin 1970).

River plume dispersion involves the transport and deposition of fine sand to clay-sized materials by a coherent plume of water that moves into the lake as a surface overflow, underflow, or midflow, depending on the relative density of lake water and inflowing water. In many of the glacial lakes the inflowing water is typically cooler than the lake water and the river water loaded with suspended sediment quickly sinks and flows along the bottom of the lake. Under normal conditions such river plume dispersion distributes fine sediment into the lake, but during flood discharges high density underflows are probably the predominant inflow mechanism for most of the year in the large glacial lakes. They are particularly important in spring freshets and floods (Pickrill & Irwin 1982, 1983). Flood underflows in Lake Wakatipu may reach speeds of $\geqslant$20 cm s^{-1} and carry particulate material over 60 km downslope into the deepest basin (Pickrill & Irwin 1982). In Lakes Wakatipu, Wanaka, and Matahina, for example, such high density underflows flow along distinct systems of sub-lacustrine channels in the lake floor. In Lakes Wakatipu and Wanaka, these channel systems are extensive and traverse the gradually sloping section of the lake floor lakeward from the steep delta foreset slopes and end at the horizontal sediment surface in the central basins (Irwin 1980). In Lake Wakatipu they are up to 30 m deep, range in width from 10-100 m, and extend up to 35 km down lake.

They have steep sides and flat floors and in places are bordered by levees. Sub-lacustrine channels are also recorded in Lake McKerrow (Pickrill et al. 1981). Drowned river courses channel the underflows in Lake Benmore (Pickrill & Irwin 1986).

Fine terrigenous silts and clays brought into the lakes initially by river plume dispersion, organic detritus, and diatom frustules, gradually settle out in the quiet pelagic waters. The proportion of biogenic to terrigenous pelagic components probably varies from lake to lake, but the terrigenous component is likely to predominate in most lakes with large river inflows. Thus in Lake Matahina, for example, biogenic components (mainly diatoms) make up only 10-20% of the basinal muds (Phillips & Nelson 1981). In Lake Rotoma, however, where there is effectively no river input, sedimentation in the lake basins has been dominated by a steady rain of diatom frustules, the bulk of the subordinate terrigenous sediment being supplied by infrequent inputs of volcanic ejecta (Nelson 1983). This is probably also true for Lake Taupo and Lake Rotoiti (N.I.), (see Lister 1978 and Craig 1985).

Sediment texture and composition

The combined operation of the four main sedimentation mechanisms results in a typical spatial distribution of surficial sediment textures in the larger glacial lakes and the reservoirs, broadly related to distance from the active river inflow. In deltaic areas, sediments are relatively coarse gravels and sands and muddy sands. Beyond the delta, sediments become progressively finer down the lake (e.g., Irwin 1975b, 1978; Pickrill et al. 1981; Pickrill & Irwin 1983). This pattern is also evident in Lake Benmore, but here the sediments are notably finer than in the other lakes studied because upstream lakes entrap the bedload and coarser suspended sediments (Pickrill & Irwin 1986). On the basis of the downlake variations in surficial sediment textures in Lake Matahina, Phillips and Nelson (1981) defined three major depositional subenvironments from river to deep lake: fluvial, (pro-)deltaic, and basinal. These are summarised in Fig. 17.

In Lake Rotoma, with no major inflows, sediments fined from sand-gravel mixtures nearshore to silts in basinal areas (Nelson 1983). This trend reflects an increasing content of diatoms with increasing water depth because of progressively less dilution by fine terrigenous sediment washed in from the catchment, and the greater deposition of diatoms in deeper water. This pattern of spatial textural composition broadly occurs also in Lake Waahi and Rotoiti (N.I.), with only moderate river inflows, and to central and northern parts of Lake Taupo (Lister 1978; Craig 1985; Schicker et al. 1986), and relates chiefly to differences in water depth, shoreline geology and morphology, and degree of wave exposure. Nelson (1983, p.201) erected a model of five process-age sediment categories in Lake Rotoma based on the different origins (age) and dispersal of the sediment, and the model probably applies to other New Zealand lakes with little or only moderate inflow.

Cores from basinal areas in a number of lakes show discrete sand layers or lenses (e.g., Wakatipu, Falls Dam, Matahina), which are usually thickest in the pro-deltaic areas, thinning away from the deltas. These layers are generally thought to be deposited by occasional density or underflow currents generated by river floods flowing along the length of the lake (see above). In Lake Pukaki, basinal sediment cores show distinct alternating dark and light layers (rhythms), composed predominantly of clay and silt, respectively. It was not possible to determine whether the couplets were annual deposits caused by the glacial melt cycle, or whether they were the result of discrete summer floods (Irwin 1972b). In Lake Tekapo (Pickrill & Irwin 1983) both annual and semi-annual varves are deposited, the annual varve thickness and semi-annual varve frequency being determined by variations in the discharge of the Godley River. This study highlights the variability in varve structure in New Zealand, mainly a result of the country's variable oceanic climate (chapter 2), and contrasts with the strongly seasonal annual varves characteristic of lakes in higher latitude continental land masses. The basinal sediments in Lake

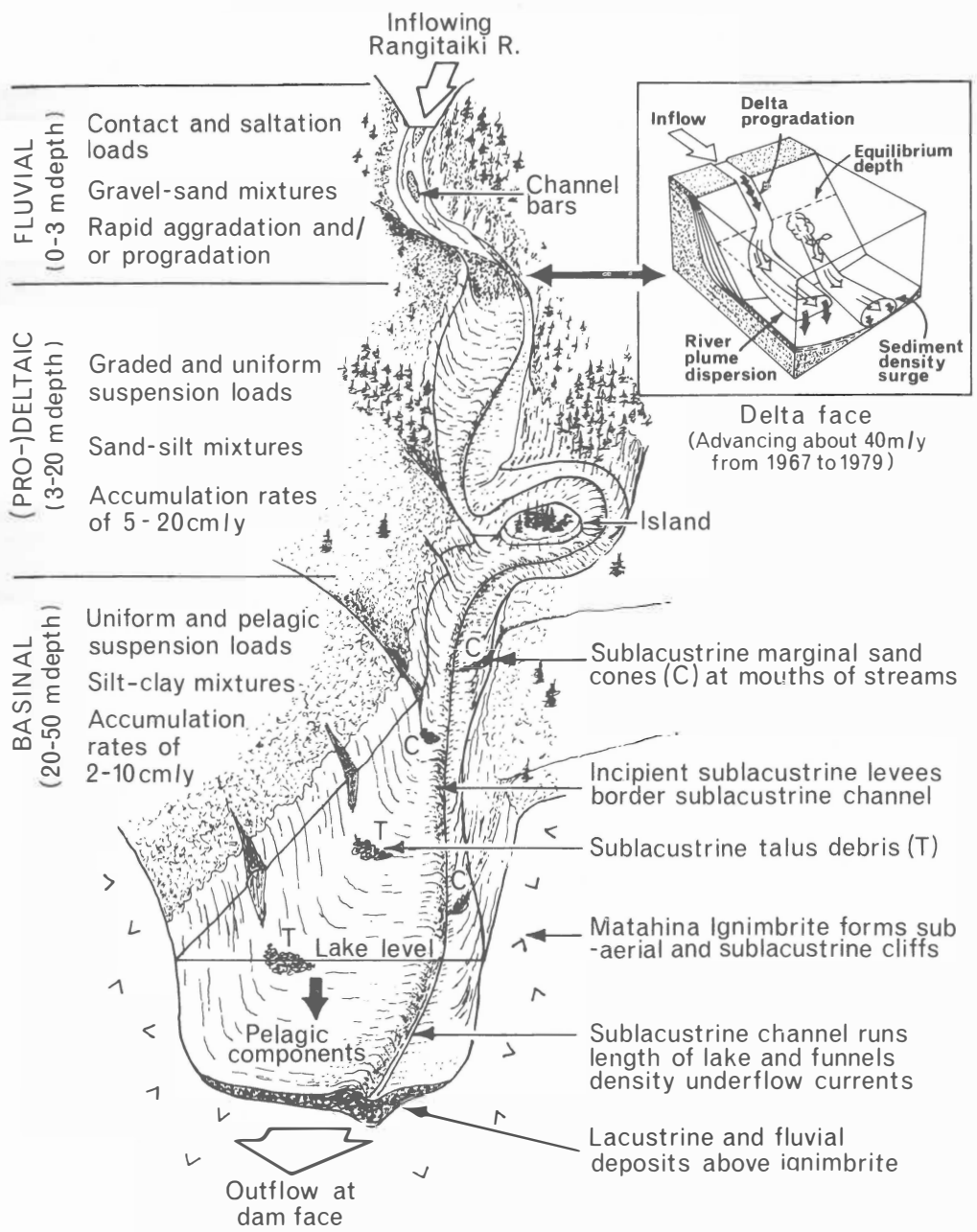


Fig. 17 Conceptual model of deposition for Lake Matahina, an artificially dammed lake on the Rangataiki River in eastern Bay of Plenty. Open arrows denote fluid motion, black arrows sedimentation. The model generally applies to other lakes in New Zealand in which sedimentation is dominated by major river inflows. (From Phillips & Nelson 1981, p.471.)

Benmore, being exceptionally clay-rich (>90%), are precluded from showing any seasonality in deposition as varves and instead form unstratified massive clay beds (Pickrill & Irwin 1986).

Relatively few detailed studies have been made of the mineralogy and geochemistry of New Zealand lake sediments (e.g., Glasby 1975; Chittenden et al. 1976; Lister 1978; Phillips & Nelson 1981; Nelson 1983; Craig 1985; Schicker et al. 1986). A wide-ranging reconnaissance survey was undertaken by Stoffers et al. (1983), who found differences in chemistry and mineralogy of lake sediments to be related chiefly to sediment lithology and the productivity of the lake waters. In general, the lake sediment compositions do not appear to be significantly influenced by humans and industrial activity although the trophic status of some lakes has been influenced by agricultural and urban developments (chapter 16). Other studies of sediment chemistry have been made in relation to nutrient recycling (e.g., McColl 1977; White et al. 1978), and in palaeolimnological studies (see below).

Sedimentation rates

There have been few determinations of sedimentation rates, and available data are summarised in Table 10. The considerable variations in sedimentation rate from lake to lake probably largely reflect variations in catchment sediment yield caused by differences in vegetation cover (e.g., Pickrill & Irwin 1980), catchment steepness and seismicity (e.g., Lister 1978; O'Loughlin et al. 1978; Pearce & Watson 1986) degree of shoreline erosion by limnic processes (e.g., Lister 1978; Pickrill & Irwin 1986), and the occurrence of high intensity, low frequency storm events which, in some lakes, produce most of the catchment sediment yield through the formation of slips and vegetation stripping (e.g., Morton Reservoir, Pickrill & Irwin 1980) (see also Crozier et al. 1982; O'Loughlin & Pearce 1982). Despite large inflows, Lake Benmore has a relatively slow sedimentation rate (3 mm yr^{-1}) because of the sediment entrappment in upstream lakes (Pickrill & Irwin 1986). Catchment area to lake area must also be a factor, but the correlation is not well known for New Zealand lakes.

Sedimentation rates can vary spatially within lakes. Rates are generally fastest at the inflow end of glacial lakes (e.g. Tekapo, Pickrill & Irwin 1983), and nearest the dam face in artifi-

Table 10 Sedimentation rates in some New Zealand lakes.

Lake	Type*	Rate (mm yr^{-1})	Reference
Arapuni	D	4 - 11	Pickrill et al. (1984)
Matahina	D	20 - 170 (av. 94)	Phillips & Nelson (1981)
Upper Karori	D	c.17	Vidal & Maris-McArthur (1973)
Morton Dam	D	c.20	Pickrill & Irwin (1980)
Falls Dam	D	10 - 15	Bishop et al. (1984)
Kaurarau Dam	D	c.174	Daly et al. (1976)
Benmore	D	3	Pickrill & Irwin (1986)
Rotorua	V	0.4 - 0.7	Pickrill et al. (1984) (after Fish 1979)
Rotoma	V	0.2 - 1.7	Nelson (1983)
Taupo	V	0.3 - 1.4	Lister (1978)
Rotoiti	V	1.0 - 2.3	Craig (1985)
Maratoto	RP	0.1 - 0.2	Green & Lowe (1985)
Waahi	R	0.5 - 1.0	Schicker et al. (1986)
Tekapo	G	10	Pickrill & Irwin (1983)
Pukaki	G	14	Irwin & Pickrill (1983)
Matiri	L	c.7	Adams (1981)
Poukawa	TP	1.3	Harper et al. (1986)

* See Table 2 and Appendix B for abbreviations.

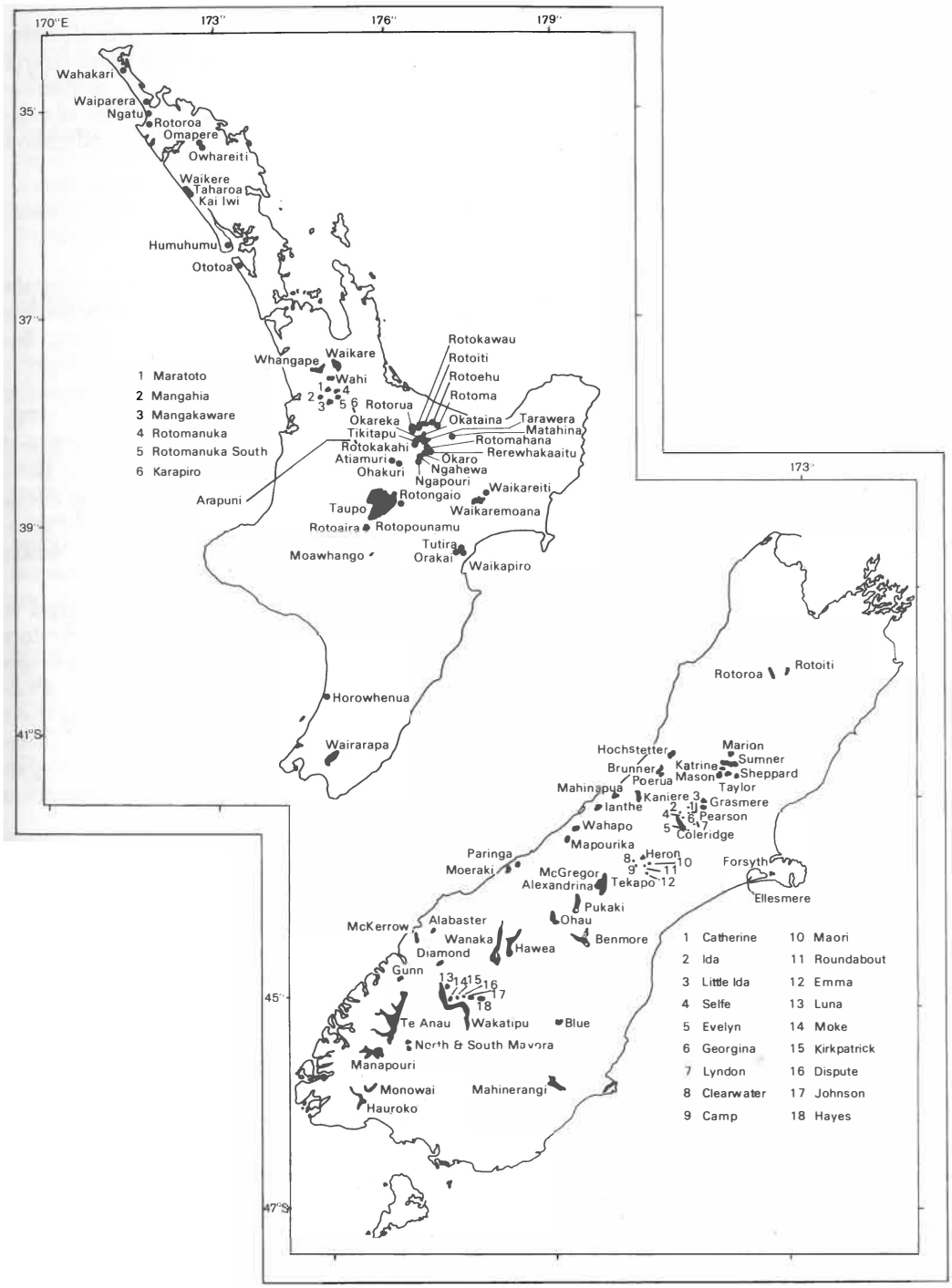


Fig. 18 Lakes in New Zealand for which bathymetric maps have been published (N.Z. Oceanographic Lake Series charts). (From Gordon 1986, p.27.) Note: **Wahi** should read **Waahi.**

cially dammed lakes (e.g., Pickrill & Irwin 1980; Phillips & Nelson 1981; Bishop et al. 1984; Pickrill & Irwin 1986), although in Lake Arapuni sediment cover is thickest in the broad central reach of the lake rather than behind the dam (Pickrill et al. 1984). In Lake Taupo, sedimentation rates are fastest ($\geqslant$1.4 mm yr $^{-1}$) in the southern part of the lake, mainly because of sediment input from the Tongariro River, but slower ($\leqslant$0.3 mm yr $^{-1}$) in the northern and central basinal areas (Lister 1978).

PALAEOLIMNOLOGY

Palaeolimnological studies in New Zealand are still in their infancy. However, there are certain features that make New Zealand lakes, particularly those in the North Island, attractive for such studies. The products of the successive eruptions from the TVZ and other volcanic districts act as time stratigraphic markers in the lake sediments. The ages of many of these tephras are accurately known (e.g., Table 1), and the tephras can be readily identified using diagnostic mineralogical and chemical criteria (Pullar et al. 1977; Howorth et al. 1980; Lowe et al. 1980; Green & Lowe 1985; Lowe 1986a,b). The tephras are known predominantly from North Island sites, but significant occurrences have also been recorded in the South Island (e.g., Kohn 1979; Robertson & Mew 1982). The 1886 Tarawera eruption, although not widespread, provided a particularly useful marker layer in the Rotorua area lakes because its deposition broadly coincides with the onset of major human disturbances affecting lake history (e.g., Fish 1979; Nelson 1983; Rawlence 1984; Craig 1985).

The late Holocence history of Lake Poukeawa (Hawke's Bay) was studied by Harper et al. (1986) using diatoms, particularly *Fragilaria* spp., which they found to be useful indicators of catchment erosion. Increased catchment erosion reflected deforestation caused by Polynesian and European settlement. Planktonic and epipelic, but not epiphytic, diatoms became more abundant following the deposition of tephras in the lake, response attributed to the fertilising effect of the tephras. Tephra Layers, including Taupo and Waimihia (Table 1), found in the peat alongside this lake have also been useful in a variety of studies (Pullar 1970; McGlone 1978; Froggatt & Howorth 1980; Howorth et al. 1980) including Maori archaeology. (Polynesian settlement in New Zealand first took place about 1000 years ago).

Studies on the record of diatoms and pigments in recent sediments in Lakes Taupo and Rotorua, based on ^{210}Pb dates, are reported by Rawlence & Reay (1976) and Rawlence (1984). Rawlence (1984) investigated possible cyclomorphosis in *Asterionella formosa* in ^{210}Pb-dated sediment cores, and in water samples, from Lake Taupo. His combined results suggest a series of irregular changes in frusule length rather than a repeating cycle of change within a fixed range of frustule length.

A number of the Waikato lakes, which contain the longest and most-complete sequence of tephras yet investigated in New Zealand lakes, have been the focus of various palaeoenvironmental studies. These have looked at changes in the lakes and their catchments over the last c.17 000 years using the tephras and pollens, pigments, diatoms, animal microfossils, and sediment characteristics including ^{13}C variations (Green 1979; Boubee 1983; Green et al. 1984; Green & Lowe 1985; Lowe 1985, 1986c; McCabe 1985; see also Fig. 14). Boubee (1983), following Deevey's (1955) early study on chironomid occurrence in Pyramid Valley sediments in the South Island, investigated chironomids in the sediments of Lake Maratoto. From a knowledge of these insects' current ecology and using cluster analysis he showed that the lakes' environment, hence its ecology, has passed through 12 main changes since c.17 000 years B.P. The results from this and the other palaeoecological studies noted above indicate that postglacial climatic changes are probably responsible for the observed pattern of changes in the lakes. Magnetic secular variations have been measured recently in cores from Lake Rotokauri (Plate 10; Kellett 1985).

Climatic change during the Holocence has been investigated through the pollen record found in peaty lake sediments adjacent to Lake Rotorua at Holdens Bay (Kennedy et al. 1978; McGlone 1983c).

A deep-drilling project investigating sediments within the Poukawa Basin (in which Lake Poukawa lies) in Hawke's Bay was started in 1980 to provide a potentially long and detailed record of late Quaternary palaeoenvironmental changes (Robinson et al. 1984). In Northland, a joint Japanese-New Zealand coring project on Lake Omapere has similar aims, notably the correlation between glacial-interglacial transitions in the Northern and Southern hemispheres (Horie 1979; Low 1984). Substantive results from both these projects are not yet available.

BATHYMETRY AND MORPHOLOGY

The bathymetry of many of New Zealand's lake basins is very well known (e.g., see Fig. 10). Most of the surveying has been done by the New Zealand Oceanographic Institute and published as the New Zealand Lake Chart series (e.g., Irwin 1967, 1969 and onwards). All of New Zealand's major lakes have been sounded in detail as shown in Fig. 18 (114 in total, Gordon 1986). This good bathymetric coverage means that the chief morphological features of the lake types are also well known. (Some general features were briefly noted in the preceding sections.) These have been reviewed by Irwin (1972a, 1975b) (see also Healy 1975a; Gage 1975; Pickrill 1978). However, morphometric parameters other than length, width, and area are generally not well known (Appendix B). An inventory by Livingstone et al. (1986) includes data on lake and catchment characteristics of 81 North Island and 84 South Island lakes.

Based on area, the largest lake in New Zealand is Lake Taupo (623 km²) in central North Island, but the next eight largest occur in the South Island (Te Anau, 348 km², is second, and Wakatipu, 289 km², third largest)(Appendix B). Thirteen of the twenty largest lakes by area occur in the South Island. The deepest lakes (all glacial) occur in the South Island, including Lake Hauroko (462 m), Lake Manapouri (444 m), Lake Te Anau (417 m), Lake Hawea (384 m), and Lake Wakatipu (380 m). The deepest North Island lakes are Lake Waikaremoana (248 m), Lake Taupo (163 m), and Lake Rotomahana (112 m). Refer to Appendix B for further data.

The total area of New Zealand's lakes is about 3400 km². This represents c.1.3% of the total land area. North Island lakes total c.1200 km² (1% of land area); South Island lakes total c.2200 km² (1.5% of land area). By volume, the South Island lakes account for virtually all of the freshwater stored in lakes in New Zealand.

SUMMARY

New Zealand's active tectonic regime, its recent volcanicity, and the effects of repeated Pleistocene glaciations, have produced an earthquake-prone, generally rugged and youthful landscape. Volcanism in the North Island, glacial activity in the South Island, rapid denudation by mass movement in the mountains and hill country, extensive alluvial aggradation in basins and lowlands, and active coastal processes, particularly on the exposed western coastline of the North Island, are the predominant geological processes that have given rise to an abundance and wide variety of lake types within a small land area. The broadly localised distribution pattern of these geological processes has resulted in the geographical grouping of ten main lake types (Table 2) into distinct lake districts (Appendix A): volcanic lakes are restricted to the North Island, glacial lakes to the South Island; wind-formed dune lakes occur mainly along the west coast of the North Island; and river-formed lakes are prevalent on the flood plains of the major river systems of both islands. The North Island has a predominance of small wind and river-formed lakes and of volcanic lakes mainly in the central volcanic region (Table 3A). The South Island has a predominance of glacial lakes, many at high altitudes, and of river-formed lakes (Table

3B). Of the total of 776 lakes in New Zealand with at least one axis ⩾0.5 km long, glacial lakes (38%), river lakes (16%), wind-formed lakes (15%), and man-made lakes (8%) account for 77%, the rest comprising landslide (5%), volcanic (4%), barrier-bar (4%), and tectonic, phytogenic, and karst lakes (<1% each), and lakes of uncertain origins (9%). Many lakes have multiple origins and have been affected by various processes after their initial formation so that complex developmental histories have ensued.

The majority of the lakes are young, and many are aged between c.5000 and c.10 000 years. Some are older e.g., the Waikato river lakes (c.16 000 years) and a few of the wind-dune and volcanic lakes (⩾c.50 000 years), and some are younger e.g., several volcanic lakes, probably all of the landslide lakes, and many of the river, wind, and barrier-bar lakes (Tables 4–9). Almost all the man-made lakes have been formed this century.

Most published studies on sedimentation in New Zealand lakes have been done on glacial lakes and man-made lakes, usually with headwater inflows. In these, sediment inputs and distribution take place through delta progradation, sediment density surges, river plume dispersion, and pelagic settling. These mechanisms produce certain surficial textural distribution patterns: in lakes with major river inflows, the dominantly terrigenous sediments become progressively finer down the lake from fluvial to deltaic to basinal subenvironments (Fig. 17); lakes with little inflow contain a greater proportion of biogenic sediment (chiefly diatom frustules) and textures generally grade from coarse to fine from near-shore to off-shore environments. The strongly seasonal annual varves (rhythms) typical of many Northern Hemisphere continental lakes are generally absent in New Zealand lakes, which contain rather variable varve structures. Sedimentation rates are variable, those in glacial lakes and some man-made lakes generally being $10\text{-}10^3$ times faster than in other lake types (Table 10).

Palaeolimnological studies in New Zealand have only begun in the last few years. Almost all have been done in the North Island where the studies have been implemented by well-dated tephra layers contained in the lake sediments that provide a time stratigraphic framework.

The bathymetry and morphology of the lake basins are generally well known, all the major lakes having been surveyed in detail (Fig. 18; Appendix B).

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