Reference: Lowe, D.J.; Green, J.D. 1992. Lakes. Pp.107-143
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Longman Paul, Auckland.

5

Lakes

D J Lowe and J D Green

INTRODUCTION

Lakes have always held an aesthetic fascination for people; they figure prominently in both art and literature and have even been endowed with spiritual qualities. For example, the nineteenth century American writer Henry D. Thoreau (1854) considered a lake to be 'the landscape's most beautiful and expressive feature. It is the earth's eye; looking into which the beholder measures the depth of his own nature'. More prosaically, lakes are also of considerable geomorphological interest as dynamic landforms originating in varied and often complex ways.

A lake can be defined generally as a body of standing water occupying a basin and lacking continuity with the sea (Forel, 1892), and forms when a process, or processes, produce a depression surrounded on all sides by a rim higher than the deepest enclosed point. The processes involved are 'constructive' when the rim is actively built, 'destructive' when the basin is excavated, and 'obstructive' when a pre-existing valley or depression is dammed (Hutchinson, 1957). A variety of geological processes can act in these ways to form lake basins — eg, tectonism, volcanism, glaciation, wind and river action, and landslides — each producing a distinctive type of lake. In New Zealand, the great variety of geological processes (chapter 1) has resulted in a corresponding wide array of lake types. Thus, New Zealand perhaps has a greater variety of lake types in a small area than any other country.

Table 5.1 Classification of New Zealand lakes based on mode of formation. After Lowe and Green (1987a).

Lake type	*Mode of formation*
Glacial (G)	Glacial activity
Volcanic (V)	Volcanic activity
Dune (D)	Wind action
Riverine (R)	River action
Landslide (L)	Landsliding
Barrier-bar (B)	Current or wave action on shorelines
Tectonic (T)	Faulting or folding
Solution (S)	Dissolution of carbonate rocks
Peat (P)	In peat or by peat accumulation
Artificial (A)	Human activity

CLASSIFICATION AND DISTRIBUTION

Various classifications of lake origins have been suggested, the most comprehensive being that of Hutchinson (1957) who defined 76 modes of origin based on the final geological process that allows the basin to hold water. This is essentially the approach that has been adopted to classify New Zealand lakes (eg, Irwin, 1975a, b; Lowe and Green, 1987a), although these classifications utilise fewer, deliberately generalised categories because many New Zealand lakes have originated by a combination of processes. The categories do correspond broadly to the major divisions of Hutchinson's classification, however. The classification adopted by Lowe and Green (1987a) is shown in Table 5.1.

New Zealand lakes are grouped into rather distinct lake districts because of the dominance of

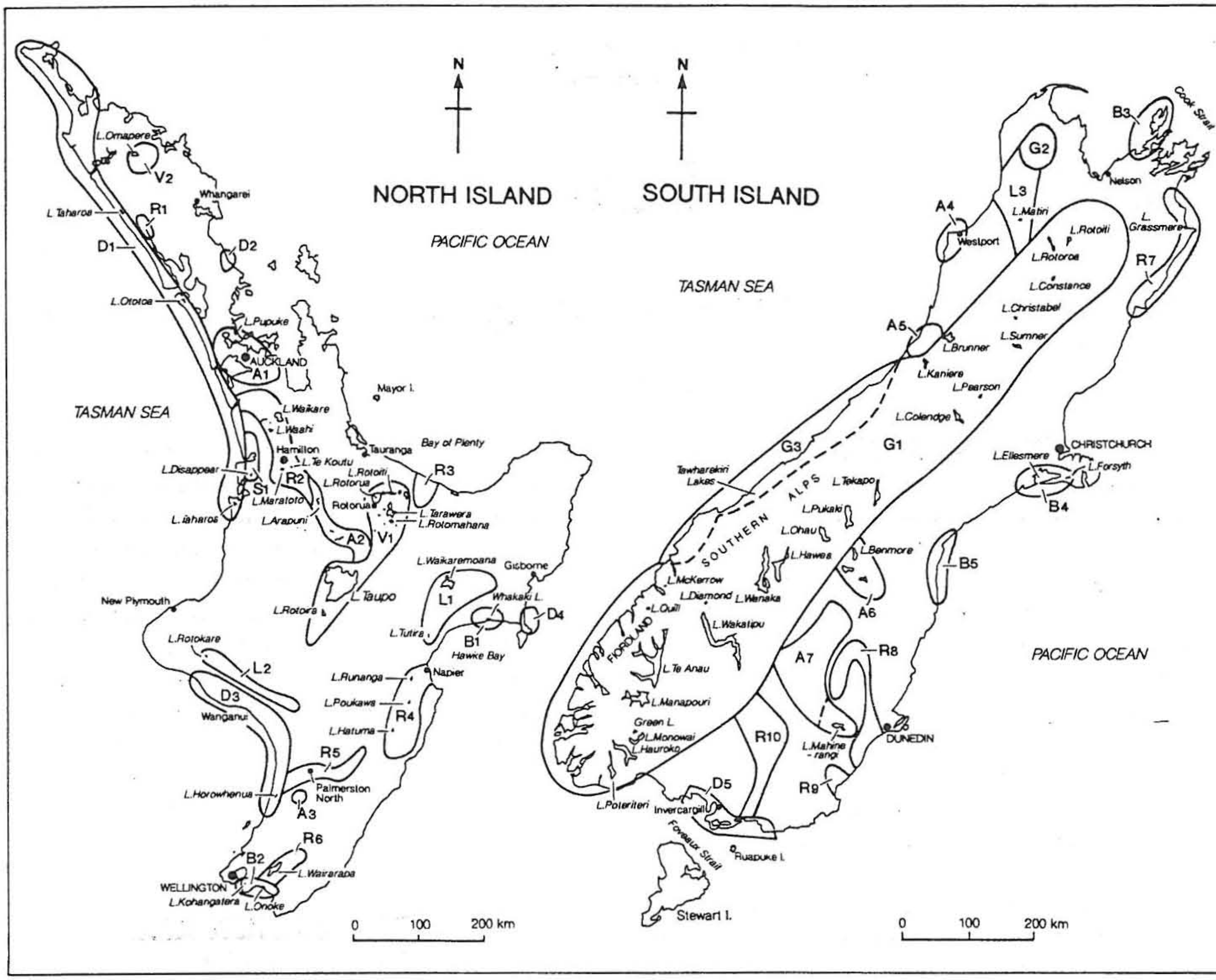


Figure 5.1 The generalised grouping of lakes in New Zealand into districts reflecting the predominance of particular geological processes. D1, Northland-Auckland-Waikato dune lakes; D2, Mangawhai dune lakes; S1, Waitomo solution lakes; D3, Wanganui-Manawatu dune lakes; D4, Gisborne dune lakes; D5, Southland dune lakes; V1, Rotorua-Taupo volcanic lakes; V2, Northland volcanic lakes; R1, Kaihu riverine lakes; R2, Waikato riverine lakes; R3, Bay of Plenty riverine lakes; R4, Hawke's Bay riverine lakes; R5, Manawatu riverine lakes; R6, Ruamahanga riverine lakes; R7, Wairau riverine lakes; R8, Tairei riverine lakes; R9, Balclutha riverine lakes; R10, Mataura riverine lakes; G1, Alps' glacial lakes; G2, Tasman glacial lakes; G3, Westland glacial and river-modified glacial lakes; A1, Auckland reservoirs and volcanic lakes; A2, Waikato hydrodam lakes; A3, Manawatu reservoirs; A4 and A5, Westland reservoirs; A6, Waitaki hydrodam lakes; A7, Clutha hydrodam lakes; B1, Hawke Bay barrier lakes; B2, Palliser Bay barrier lakes; B3, D'Urville barrier lakes; B4, Christchurch barrier lakes; B5, Timaru barrier lakes; L1, Wairoa landslide lakes; L2, Wanganui landslide lakes; L3, Karamea landslide lakes. After Green and Lowe (1987).

particular geological processes in certain areas (Figure 5.1). Thus, 'glacial lakes' are found only in the South Island, and 'volcanic lakes' occur only in the North Island, particularly in the Central Volcanic Region; wind-formed 'dune lakes' are most common along the west coast of the North Island; 'riverine lakes' are clustered on the flood plains of the major rivers; 'landslide lakes' are usually associated with hilly or mountainous terrain, particularly in regions subject to earthquakes; 'solution lakes' occur in areas composed of carbonate rocks (limestone and marble); and 'barrier-bar' lakes are developed along coastal and lake shorelines.

Excluding offshore islands, New Zealand has a total of about 775 lakes with lengths of 0.5 km or more (476 in the South Island and 299 in the North Island; Table 5.2). Glacial lakes are the most common (38%), followed by riverine lakes (16%), dune lakes (15%), and artificial lakes (8%), which together comprise 77% of all lake types. The rest include landslide (5%), volcanic (4%), barrier-bar (4%), tectonic, peat, and solution lakes (< 1% each), and lakes of uncertain origin (9%). In the South Island, glacial and riverine lakes predominate. Glacial lakes are mostly at high altitudes (> 600 m asl; Irwin, 1975a; Lowe and Green, 1987a) and most are small. In the North Island, dune and riverine lakes are the most common types, occurring at low altitudes (< 90 m). Most of the volcanic lakes of the Central Volcanic Plateau are at higher elevations (> 275 m) and, on the average, are larger than other North Island lake types.

MORPHOMETRY AND BATHYMETRY

Size-related measurements (morphometry), including area, depth, length, width, and mean depth, for 163 New Zealand lakes are summarised by Lowe and Green (1987b). Irwin (1975a, b) and Livingstone *et al* (1986) also list useful data, with Livingstone *et al* (1986) also giving information on catchment characteristics.

New Zealand's largest lakes are listed in Table 5.3. The largest is Lake Taupo (623 km^2) in the central North Island, but the next eight occur in the South Island (Lake Te Anau, 347 km^2, is second; and Lake Wakatipu, 289 km^2, third). Thirteen of the 20 largest lakes occur in the South Island. The deepest lakes are all glacial, and include Lakes Hauroko (462 m), Manapouri (444 m), Te Anau (417 m), Hawea (384 m), and Wakatipu (380 m). Lakes Hauroko and Manapouri are the 16th and 22nd deepest lakes in the world, respectively (cf. Herdendorf, 1984). The deepest North Island lakes are Lake Waikaremoana (248 m), Lake Taupo (185 m), and Lake Rotomahana (112 m).

New Zealand lakes cover a total area of approximately 3400 km^2, representing about 1.3% of the land area. The total area of North Island lakes is about 1200 km^2 (1% of the land area) and South Island lakes total about 2200 km^2 (1.5% of the land area).

The bathymetry (bottom contours) of New Zealand's major lakes is well known as a result of surveys carried out mainly by the New Zealand Oceanographic Institute and published since 1967 as the *New Zealand Lake Chart Series* or *Miscellaneous Series*. Bathymetric maps are available for at least 124 lakes, most listed by Thompson (1989).

AGES

Lakes are transitory features of the landscape. After their initial formation they are eventually infilled by sediments and so few lakes world wide are older than about 1 million years. Most are much younger, having been formed in the late Pleistocene or Holocene, and this is true of New Zealand where the landscape is youthful and still actively developing (see chapter 2). Most of the lakes are thus very young in geological terms, commonly being between 5000 and 10 000 years old. Details of lake ages are discussed in the following sections.

Table 5.2 Frequency of lake types in New Zealand. Only lakes with lengths 0.5 km or more are included. After Lowe and Green (1987a).

Type	*North Island*		*South Island*		*Total*	
	Number	*%*	*Number*	*%*	*Number*	*%*
Glacial	0	0	289	60	289	38
Volcanic	30	10	0	0	30	4
Dune	106	35	13	3	119	15
Riverine	67	22	54	11	121	16
Landslide	18	6	22	5	40	5
Barrier-bar	14	5	18	4	32	4
Tectonic	6	2	0	0	6	1
Solution	1	<1	0	0	1	<1
Peat	0	0	0	0	0	0
Artificial	34	11	31	7	65	8
Undetermined	23	8	49	10	72	9
Totals	299		476		775	

FORMATION AND DEVELOPMENT

The formation and development of New Zealand lakes were comprehensively reviewed by Lowe and Green (1987a). The following accounts are based on this review with the addition of new information.

Glacial Lakes

Glacial lakes are found exclusively in the South Island because of the extensive glacial action and reworking of resultant debris there during the Pleistocene glaciations when large, often coalescing valley glaciers and alpine ice caps covered most of the Southern Alps (chapter 2; Suggate, 1990). Most of the lake basins have formed by more than one mechanism and many have been modified later by non-glacial processes such as alluvial aggradation, faulting, landsliding, or coastal processes (Gage, 1975). Usually these lakes may still be classified as glacial because they originated as a direct consequence of glacial activity. Because of such typically complex origins, Gage (1975) grouped New Zealand glacial lakes into four generalised types:

1 Lakes in ice-excavated rock depressions. These comprise two main types. 'Cirque lakes' occupy amphitheatres formed by ice action (frost riving or freeze-thaw action) at the heads of glaciated valleys, usually at higher elevations. Although commonly small and comparatively shallow, some are very deep relative to their surface area. 'Piedmont lakes', usually at lower elevations, occupy long, narrow, greatly-overdeepened U-shaped valleys produced by large valley glaciers, and include 'fjord lakes' near coastlines. Elsewhere in the world, the action of continental ice sheets may produce very large lakes (eg, the Great Lakes of North America), but such lakes are not found in New Zealand.

2 Lakes partly or completely enclosed by moraine or associated fluvioglacial outwash deposits. These include the small but abundant 'kettle lakes' formed in depressions in moraine caused by the collapse of deposits following melting of large blocks of ice which have been left by receding glaciers.

3 Combinations of (1) and (2) modified by non-glacial processes (eg, damming by alluvial fans or wind-blown dunes).

4 Lakes adjacent to modern glacier ice ('ice-margin' or 'pro-glacial lakes'); these are usually temporary, but commonly recur (eg, associated with the Franz Joseph, Lyell, and Douglas Glaciers; Gage, 1975, 1980).

In New Zealand, the term 'tarn' (a Scandinavian word for a small mountain lake) is frequently used for any small glacial lake. Such lakes may be cirque or kettle lakes, or small lakes in hollows produced by glacial corrasion.

The basins of many New Zealand glacial lakes, of all sizes, may primarily be ice-excavated rock depressions in which the water is held by a rock lip but further deepened by moraine or fluvio-glacial outwash dams. Few are likely to be retained by solid rock alone (eg, Figure 5.2; Gage, 1975). Lake Wakatipu, for example, with a maximum depth of 380 m, is held by a rock rim about 305 m high capped with about 75 m of till (Bayly and Williams, 1973). However, moraines around the ends of some large, ice-gouged lakes may be only minor features and contribute little to their depth (eg, Lakes Rotoiti and Rotoroa). Examples of smaller, essentially rock-impounded lakes include Hawdon and Letitia (Gage, 1958, 1959).

In the upland areas of northwest Nelson, the Southern Alps, and Fiordland, there are many small tarns and some larger lakes lying in the concave excavated floors of cirques and depressions (Figures 5.3 and 5.23). Examples include Lakes Aorere, Browne, Quill, Shirley, and Unknown. Such lakes are very abundant and hundreds of tarns occur in Fiordland alone. Most of the larger lakes occupy overdeepened valleys once filled by glaciers, and similar lakes, probably larger, existed in equivalent positions during earlier interglacials as shown by the presence of lake sediments in drill holes and outcrops. Large glaciers, some more than 30 km long, excavated the troughs now filled by Lakes Hauroko, Monowai, Poteriteri, and Te

Table 5.3 Some morphometric parameters of the 40 largest lakes by area in New Zealand. After Lowe and Green (1987b).

*Lake and location**	*Type***	*Area (km²)*	*Max depth (m)*	*Max length (km)*	*Max width (km)*	*Mean depth^π (m)*	*Max altitude^§ (m asl)*
Arapuni (A2)*	A	14 (28)†	44	7	1	nd	110
Aviemore (A6)	A	25 (23)	41	18	5	nd	268
Benmore (A6)	A	74 (12)	91	26	6	nd	360
Brunner (G1)	G	36 (18)	109 (18)#	9	7	51	85
Coleridge (G1)	G	33 (21)	200 (8)	18	3	99	507
Ellesmere (B4)	B	180 (5)	3	26	13	nd	1.5
Grassmere (R7)	B	13 (29)	<1	6	4	nd	<1
Hawea (G1)	G	141 (7)	384 (4)	42	10	nd	342
Hauroko (G1)	G	68 (13)	462 (1)	34	8	nd	155
Kaniere (G1)	GL	13 (30)	198 (9)	9	3	nd	133
Mahinerangi (A7)	A	19 (25)	30	22	3	6	391
Manapouri (G1)	G	153 (6)	444 (2)	28	12	100	179
Mapourika (G3)	G	8 (38)	78	5	4	nd	75
Mavora, N. (G1)	G	11 (36)	77	10	2	nd	626
Monowai (G1)	G	33 (22)	161 (11)	21	3	nd	206
McKerrow (G1)	GB	18 (26)	121 (15)	15	2	nd	3
Ohau (G1)	G	61 (14)	129 (14)	17	5	66	519
Okataina (V1)	V	11 (35)	79	6	5	44	311
Omapere (V2)	V	12 (33)	2	5	4	nd	240
Poteriteri (G1)	G	43 (16)	nd	27	3	nd	23
Pukaki (G1)	G	99 (8)	70	23	8	47	497
Rotoaira (V1)	V	15 (27)	15	6	4	8	564
Rotoehu (V1)	V	8 (39)	14	5	4	8	295
Rotoiti (V1)	V	34 (20)	34	15	4	33	279
Rotoiti (G1)	G	9 (37)	82	9	3	50	618
Rotoma (V1)	V	11 (34)	83	5	5	39	316
Rotomahana (V1)	V	8 (40)	112 (17)	6	3	51	339
Rotoroa (GI)	G	21 (24)	145 (12)	14	3	97	451
Rotorua (VI)	V	80 (11)	45	12	10	10	280
Sumner (GI)	G	12 (32)	135 (13)	10	2	nd	524
Tarawera (V1)	V	41 (17)	88	11	9	57	298
Taupo (V1)	V	623 (1)	185¥ (10)	41	30	98	357
Te Anau (G1)	G	347 (2)	417 (3)	60	29	nd	203
Tekapo (G1)	G	88 (9)	120 (16)	25	6	69	710
Waikare (R2)	R	35 (19)	2	10	6	nd	9
Waikaremoana (L1)	L	56 (15)	248 (7)	16	11	93	581
Wairarapa (R6)	R	81 (10)	2.5	18	10	1.5	2
Wakatipu (G1)	G	293 (3)	380 (5)	75	6	210	309
Wanaka (G1)	G	193 (4)	311 (6)	46	12	nd	277
Whangape (R2)	R	12 (31)	3	8	5	2	6

* Location given in Figure 5.1
** See Table 5.1
¥ Dr M Cryer (pers comm, 1990)
π Volume/area; nd = not determined
§ Approximate as some lake levels fluctuate
† Ranking according to area in parentheses
# Ranking according to depth in parentheses (deepest 18)

Anau in Southland; Hawea, Ohau, Wakatipu, and Wanaka in Otago; Coleridge (Figure 5.4), Pukaki, and Tekapo in Canterbury; and Rotoiti and Rotoroa in Nelson (Figures 20.11, 21.6 and 23.6). At the same time, other glaciers gouged out the deep, U-shaped valleys now forming the fjords of Fiordland. It is likely that during the coldest part of the Last Glacial (Otira) many of these fjord valleys contained deep oligotrophic lakes impounded by shallow sills. However, because of rapidly rising sea levels between about 9500 and 8000 years ago, sea water overtopped the sills and flooded the fjord basins (Pickrill *et al*, 1990). Lake McKerrow is an example of such a fjord lake that has persisted, although it is now tidally-influenced (Pickrill *et al*, 1981).

These large glacial lakes tend to be steep-sided. The bottoms of many of them, including Lakes Manapouri, Te Anau, and Wakatipu, lie below sea level and these zones below sea level are known as 'cryptodepressions'. The basin floors are generally flat as a result of blanketing lake sediment (Figure 5.5), although the original basin surface below the lake sediment may be rather rugged because of remnants of moraine (eg, Lake Pukaki; Carter and Carter, 1990). Since their formation many of the large glacial lakes have been considerably infilled by glacially-derived sediments deposited by the rivers flowing into

Figure 5.3 Lake Quill, a glacial cirque lake at nearly 1000 m altitude in Fiordland. A smaller, ice-covered lake lies in another cirque basin about 350 m higher. The Sutherland Falls (580 m high) are visible in the foreground. (D L Homer, DSIR Geology and Geophysics)

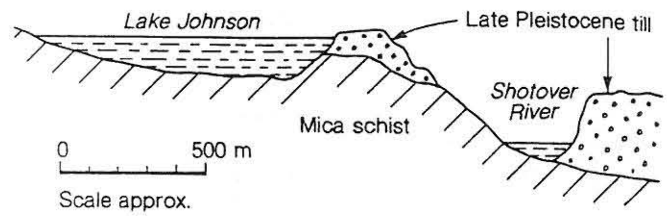


Figure 5.2 Sketch of Lake Johnson, a glacial lake in an ice-excavated rock basin at 392 m altitude near Lake Wakatipu. The lake has a maximum depth of about 27 m, and the rock rim at the outlet end is about 17 m below lake level. After Park (1909), and Lowe and Green (1987a).

them, both as deltas and basinal fill (Figure 5.6). Rates of infilling are thus fast compared with most other New Zealand lakes. Average sedimentation rates in Lakes Tekapo and Pukaki have been measured at 10 and 14 mm per year, respectively (Pickrill and Irwin, 1983; Irwin and Pickrill, 1983). Such lakes have acted as giant sediment traps, markedly reducing sediment flow down the Waitaki and Clutha Rivers to the continental shelf in the past 10 000 years (Carter and Carter, 1990).

Examples of lakes enclosed mainly by moraine include Lakes Brunner, Haupiri, Ianthe, and Mapourika in Westland, and lakes in the Mackenzie Basin. Lake Wahapo, dammed largely by moraines, is currently affected by an active alluvial fan of the Waitangitaona River (see Figure 20.7). Lake Mahinapua, near Hokitika, is dammed by ridges of moraine together with sand dunes, while nearby Lake Kaniere lies in a moraine-bound glacial basin modified by a large landslide (Bell and Fraser, 1906). Diamond Lake, to the north of Lake Wakatipu, is dammed mainly by glacial outwash sediments that were probably deposited soon after the retreat of the enlarged 'Wakatipu Glacier' (Figure 5.7). Some glacial valleys contain small groundwater lakes in enclosed hollows in small areas of ablation moraine or on undulating moraine surfaces (eg, Lakes Alexandra, Blackwater, and Clearwater in Canterbury; Gage, 1958, 1959). Lake Marymere (Figure 5.8a) is an example of a kettle lake, and occupies an enclosed depression in a old meltwater channel of the former Waimakariri Glacier. Kettle lakes have formed in recent times downstream of the receding Fox Glacier (Gage, 1980).

Many lakes throughout the South Island mountains are partly impounded by alluvial fans

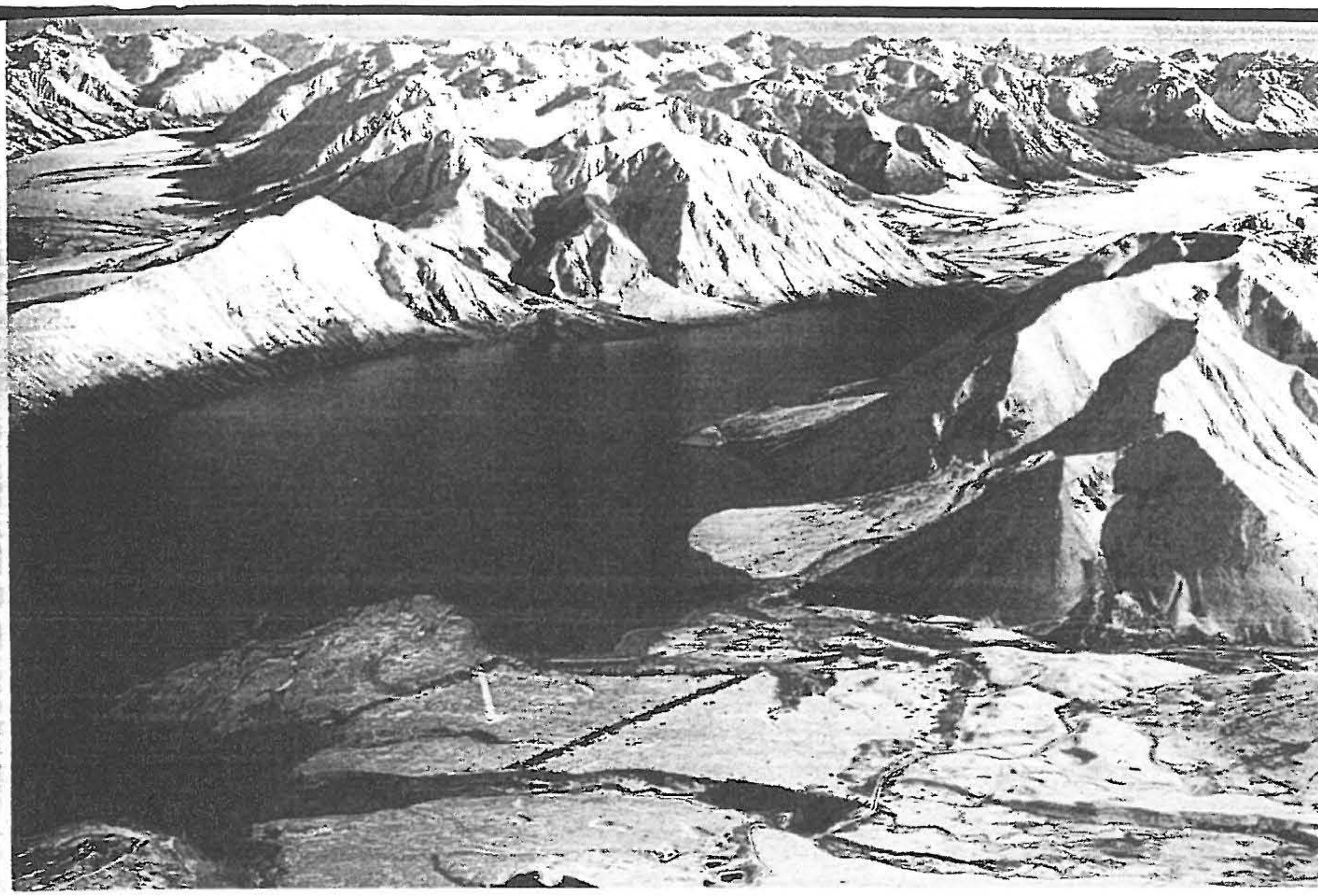
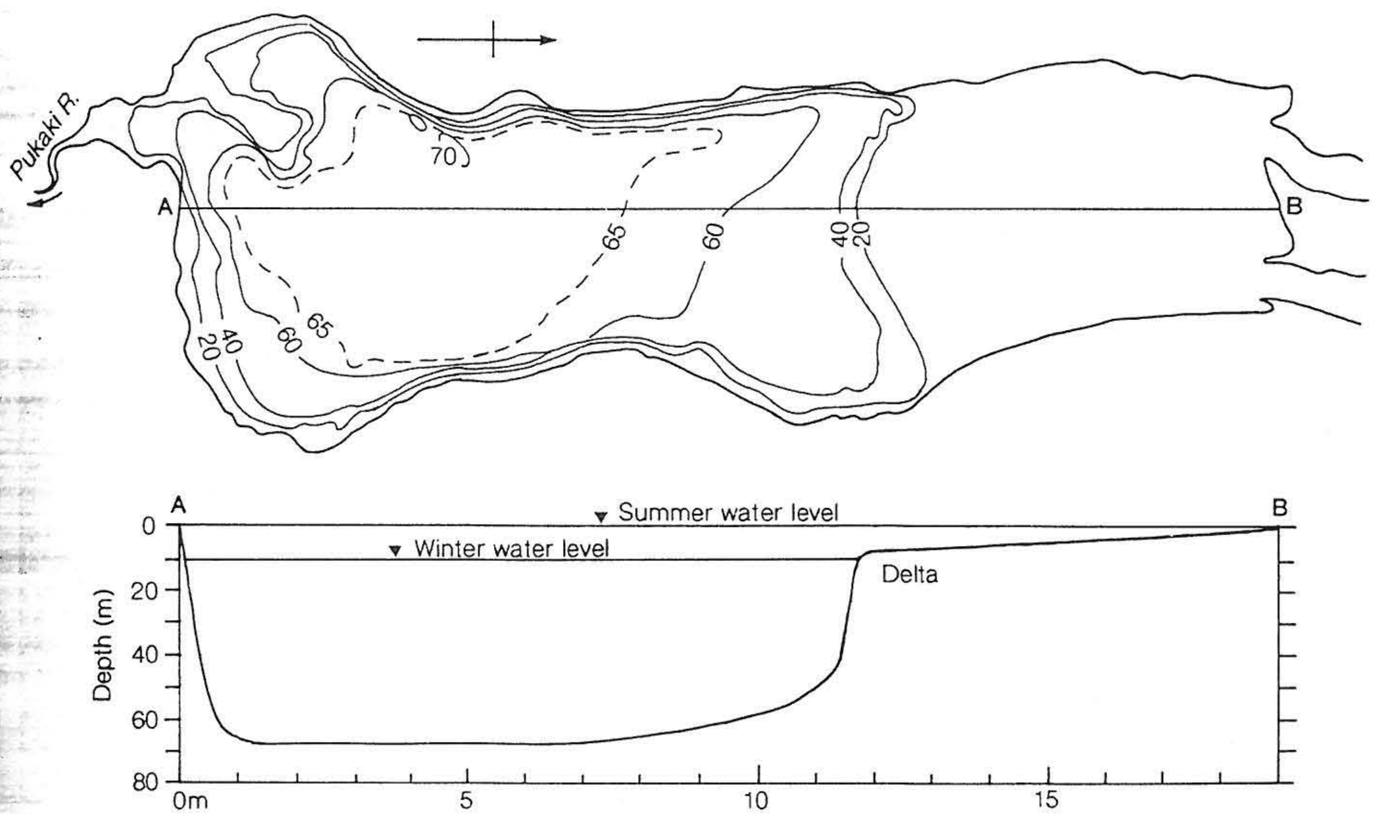


Figure 5.4 A winter view of part of Lake Coleridge, a large glacial lake occupying a glacially-carved landscape. Alluvial fan deposits can be seen around the shoreline of the lake; hummocky moraines and small kettle lakes are visible in the foreground. In the background are the Rakaia (left) and Wilberforce (right) valleys separated by the Rolleston Range of the Southern Alps. (D L Homer, DSIR Geology and Geophysics)

Figure 5.5 Generalised bathymetry (in metres) of Lake Pukaki and profile along line A–B. After Irwin (1972).



or screes, many of which are still active, especially above the tree line (see chapter 6). Earlier ones were formed and reworked by rivers into alluvial fans soon after final rapid deglaciation about 10 000 years ago, often to form or modify lake basins such as Gunn, Hawdon, Heron, Pearson, and Poreua, and Sarah (Figure 5.8a, b). Although Lake Grasmere may have formed originally behind a moraine loop, it seems to have been greatly reduced in area by the growth of alluvial fans of Cass River and Ribbonwood Creek, with the latter continuing to encroach upon the area of the lake into historic times (Figure 5.8b; Gage, 1958, 1959; Harper, 1989).

Many of the larger glacial lakes were at much higher levels in the past, as shown by stranded tiers of earlier shorelines marked by cut benches and storm-beach ridges. These earlier lakes were considerably larger in area than at present, but

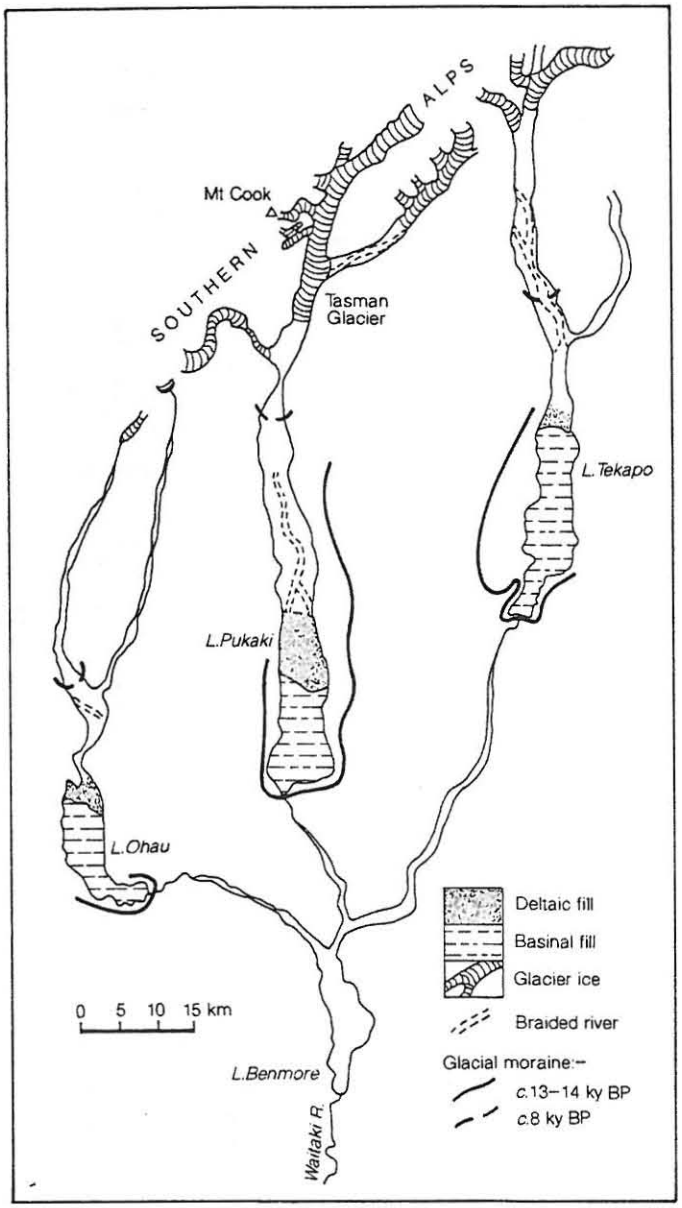
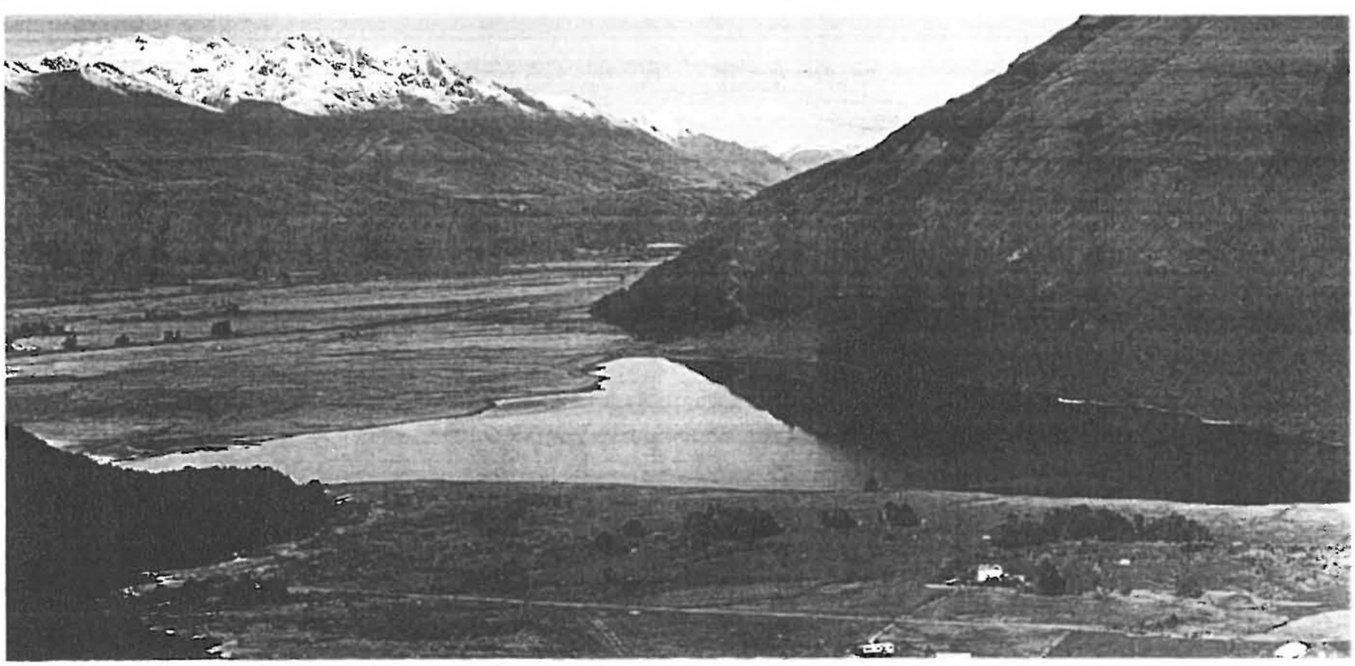


Figure 5.6 Lakes Ohau, Pukaki, and Tekapo impounded mainly behind terminal moraines. Areas of basinal infilling and deltaic sediments are also shown. Lake Benmore is an artificial hydroelectric lake. After Carter and Carter (1990).

Figure 5.7 Diamond Lake, north of Lake Wakatipu in Otago, is a glacial lake dammed against the glacierised slopes of Mt Alfred (right) and between glacial outwash sediments in the Dart (front) and Rees (back) Valleys. Stranded high lake-level shorelines flank the Richardson Mountains in the distance (National Publicity Studios, Wellington)



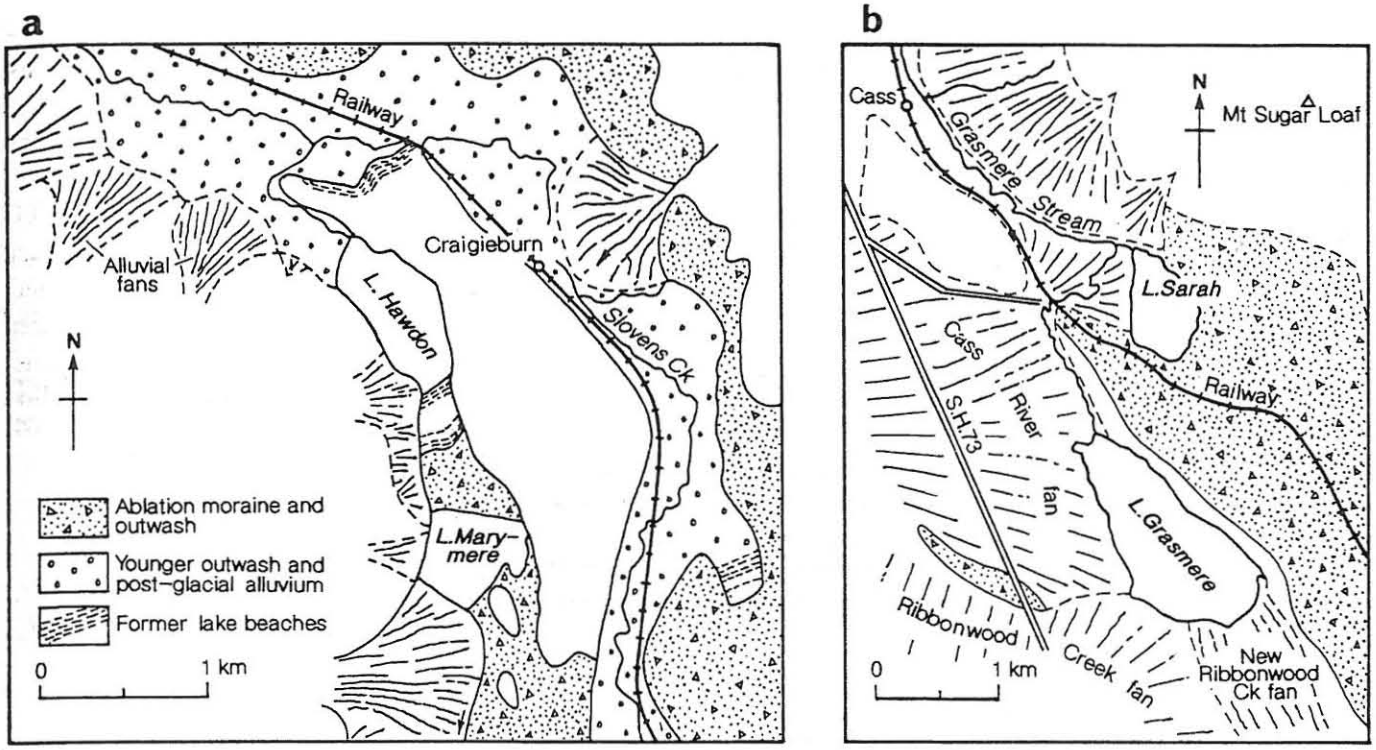
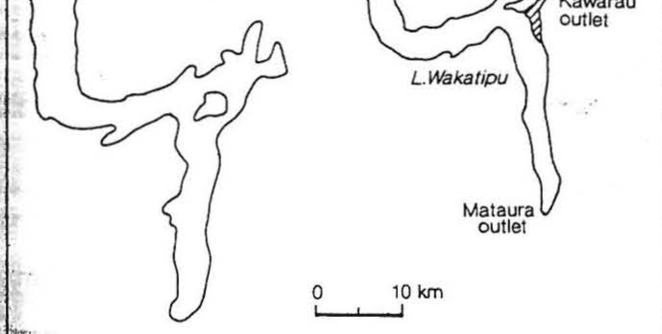


Figure 5.8 (a) Lake Hawdon, a glacial lake occupying a rock basin and partly dammed by alluvium, and Lake Marymere, a large kettle lake; (b) Lakes Sarah and Grasmere, impounded by moraine and alluvial fans. After Gage (1959).

Figure 5.9 Sketch of the enlarged glacial 'Lake Wakatipu' compared with present-day Lake Wakatipu and Lake Hayes. After Park (1909), and Lowe and Green (1987a).

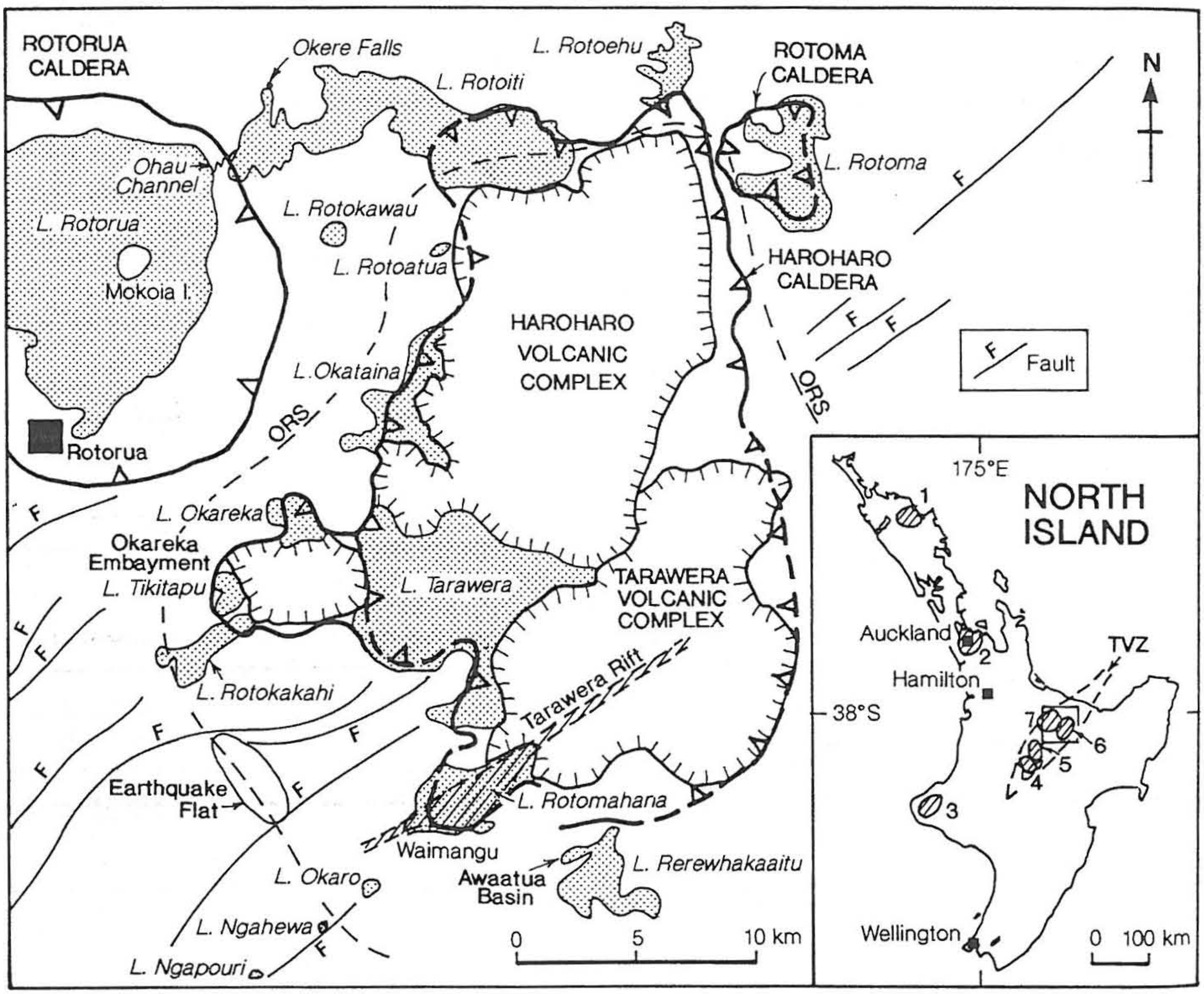


were probably short lived as a result of downcutting at the lake outlets, causing lowered lake levels (Gage, 1975). For example, Lake Wakatipu was once much larger and incorporated present-day Lakes Hayes and Johnson (Figure 5.9). Such an enlarged lake, with fluctuating levels reflecting glacier advances and retreats, may have persisted until soon after about 10 000 years ago when downcutting of the Mataura outlet exposed the Shotover Delta, thus isolating Lake Hayes (Figure 5.9). The Mataura outlet was abandoned in favour of the present outlet, the Kawarau River, possibly around 5000 years ago (Lowe and Green, 1987a; see also chapter 21). Stranded higher lake-level shorelines associated with the enlarged Lake Wakatipu are visible in Figure 5.7.

Other lakes which have been much larger include Brunner, Hawdon, Hawea, Kaniere, Manapouri, Ohau, Pukaki, Rotoroa, Rototiti, Sarah, Te Anau, and Tekapo. The stranded shorelines around Lakes Tekapo, Pukaki, Ohau, Hawea, Wanaka, and Wakatipu have progressively tilted since their formation because of different rates of tectonic uplift away from the crest of the Southern Alps. Studies on the tilting rates of these shorelines at Lake Tekapo and the other lakes indicate that over a relatively short period, starting about 10 000 years ago, there was a rapid retreat of the 'Tekapo Glacier' and a rapid down-cutting of the outlet (Wellman, 1979).

Few of the glacial lakes have been dated directly, and there have been difficulties in attaining a definitive chronology of late Quaternary glacial deposits (Burrows, 1988; Suggate, 1990). The dates that have been obtained indicate that the glacial lakes in their present form all developed at much the same time, following retreat of the glaciers at the beginning of postglacial environmental conditions, which can be recognised as early as about 15 000 years ago (Suggate, 1990). Sustained retreat of the glaciers was well under way by about 13 000 years ago and Pillans *et al* (chapter 2) have suggested that about 12 000 years ago is an appropriate age to mark the start of New Zealand postglacial time. Ice still occupied sections of many of the valleys, but the larger glacial lakes must date from near this time and Burrows (1979, 1988) gave a number of radio-

Figure 5.10 Volcanic lakes in the Rotorua area and structural and volcanic features associated with the Rotorua and Haroharo Calderas. The Haroharo Caldera lies within the Okataina Volcanic Centre (marked by the Okataina Ring Structure, ORS). Inset shows Bay of Islands-Kaikohe (1), Auckland (2), and Egmont (3) Volcanic Districts, and locations of Taupo (4), Whakamaru (5), Okataina (6), and Rotorua (7) Calderas within the Taupo Volcanic Zone (TVZ). Based mainly on Nairn (1989); inset after Cole and Nairn (1975), Wilson *et al* (1984, 1986), and Houghton *et al* (1987).



carbon dates on lake sediments from Canterbury, Westland, and Fiordland of 10 000–12 000 years age. The retreat of the glaciers continued rapidly, although interrupted by advances of ever-diminishing extent, and other lakes formed or were modified during the accompanying periods of intense erosion and fan building. This phase continued until about 9000–10 000 years ago when forests became established over most of the South Island (McGlone, 1988; Suggate, 1990). Thus, many glacial lakes are probably about 10 000–12 000 years old, but others may be older (perhaps up to about 15 000 years) or considerably younger, depending mainly on location and mode of formation. The youngest lakes may be expected to be found in areas where ice retreat was delayed longest, such as in high altitude cirques or corrasion hollows above about 1000 m.

Volcanic Lakes

Volcanic lakes are found in three main areas, coinciding with the distribution of recent volcanism — the Taupo Volcanic Zone, the Auckland Volcanic District, and the Bay of Islands-Kaikohe Volcanic District (Figure 5.10, Inset). Volcanic lakes are also found on some of the offshore islands (eg, Mayor Island, Raoul Island) and in the Egmont (Taranaki) Volcanic District. Most of the lakes in their present form are young, although in the Taupo Volcanic Zone extensive deposits of diatomite and other lake sediments show that lakes have always characterised the region as it has been low lying for most of its recorded history (eg, Grange, 1937; Healy, 1975a; Wilson *et al*, 1986; see also chapter 11).

In these areas lake basins have been formed by three major processes which may act in combination (Healy, 1975a):

1 Caldera collapse caused by magma withdrawal and faulting following massive eruptions; the result is usually a large subcircular depression, often with precipitous sides. Caldera basins are usually modified by the extrusion of lava domes.

2 Smaller explosive eruptions, producing craters. 'Ground craters' extend below the general ground level and are usually subcircular. Two main types occur: 'maars', with a surrounding rim built up of material ejected during the typically phreatomagmatic eruption, and often containing water; and others without such a rim and which commonly originate by hydrothermal eruptions. 'Volcano craters' may be found near the summits of raised stratovolcanoes (Bayly and Williams, 1973).

3 Blocking of valleys by lava flows or pyroclastic material.

The largest volcanic lakes have been formed by (1) and (3) acting together and are found within the Rotorua, Haroharo (Okataina), and Taupo Calderas (Figures 5.10 and 5.11). Radiometric dating of the pyroclastic deposits (ignimbrites and airfall tephra deposits) associated with the formation of calderas and explosion craters, and contemporaneous lava flows, has enabled the ages of the lakes to be determined in more detail than for most other New Zealand lakes (Lowe and Green, 1987a; Froggatt and Lowe, 1990).

LAKES IN THE ROTORUA AREA

Lake Rotorua (Figure 5.11) occupies the Rotorua Caldera which was formed about 140 000 years ago following the eruption of the rhyolitic Mamaku Ignimbrite (Wilson *et al*, 1984). A lake formed soon after and lake levels have fluctuated since (Figure 5.12). The highest level, about 90 m above present lake level, occurred when deposits of the Rotoiti Tephra, erupted from the Okataina Volcano about 50 000 years ago (Froggatt and Lowe, 1990), blocked the northward drainage from the lake. This level is marked by extensive terraces around the lake (see Figure 2.27). The lake level remained high until drastically lowered to near its present level about 22 000 years ago when the Rotoiti Tephra deposits were breached, and the lake drained northeastwards through the valley now partly occupied by Lake Rotoiti. The lake dropped to below its present level between about 19 000 and 9000 years ago. Subsequent changes in lake depth and area were caused mainly by growth of the Haroharo volcanic pile in the adjacent Haroharo Caldera in the Okataina Volcanic Centre (Healy, 1975a; Kennedy *et al*,

Figure 5.11 A westward-looking view across part of Lake Okataina towards Lake Rotorua lying in the Rotorua Caldera. The cliffs adjacent to the narrow arm of Lake Okataina in the foreground mark the western margin of the Haroharo Caldera (see Figure 5.10). Lavas and pyroclastic deposits associated with the Mamaku eruptive episode about 7000 years ago form the shoreline in the immediate foreground; the steep, largely bush-covered land beyond comprises rhyolite domes, lava flows, and pyroclastic deposits erupted mainly in the past c. 250 000 to 140 000 years. (D L Homer, DSIR Geology and Geophysics)

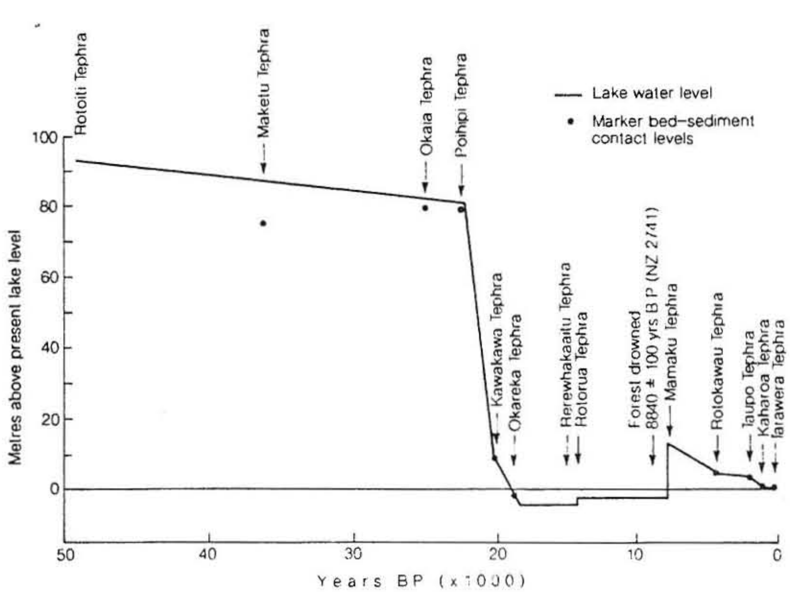


Figure 5.12 Variations in water levels of Lake Rotorua from about 50 000 years ago to the present based on dated tephra marker beds. Present lake level is 280 m above sea level. After Kennedy *et al* (1978), and Nairn and Wood (1987).

1978; Nairn and Wood, 1987). This growth progressively impeded drainage through the Haroharo Caldera, forming Lakes Rotoiti and Rotoehu, as described below, until about 7000 years ago the drainage was completely blocked by deposits of the Mamaku eruptive episode, and Lake Rotorua was forced to overflow to the north into the Okere Channel (Kaituna River) via the western part of Lake Rotoiti. Since then lake levels have steadily dropped (see Figure 2.23), probably because of downcutting at the Ohau outlet. The higher lake levels between about 7000–4000 years ago may have partly resulted from higher rainfall than at present (McGlone, 1983), while historical fluctuations in lake level of about 1.5 m are correlated not only with variation in rainfall (as in other lakes in the Rotorua area), but also with sedimentation in the outlet at Ohau Channel (Healy, 1975b).

Most of the other lakes in the Rotorua area formed in association with rhyolitic volcanism in the Okataina Volcanic Centre (Healy, 1975a; Nairn, 1989). Lake Rotoiti formed after the Rotoma eruptive episode about 8500 years ago finally blocked drainage from Lake Rotorua. The western part of the lake occupies the valley previously cut by the outflow from Lake Rotorua, while the deeper eastern end is part of the Haroharo Caldera. Lake Rotoehu occupies a series of valleys blocked by lavas of the Rotoma eruptive episode, and so has a more digitate outline, and is shallower than other volcanic lakes in the area. Lakes Tarawera and Okataina (Figure 5.11) were formed chiefly by lava damming and are impounded against the western rim of the Haroharo Caldera. As the basins of these comprise a portion of the caldera, they are deep, steep-sided, and flat-bottomed (eg, Figure 5.13). Modern Lakes Okataina and Tarawera date from about 7000 and 5000 years ago, respectively. Okataina may have had a south-draining outlet into the Tarawera valley about 7000–5000 years ago, and the Tarawera valley was probably occupied by a small lake, or lakes, before formation of the present-day lake. Lake Tarawera attained its present form about 5000 years ago when lavas associated with the Whakatane eruptive episode dammed drainage of the valley to the east (Figure

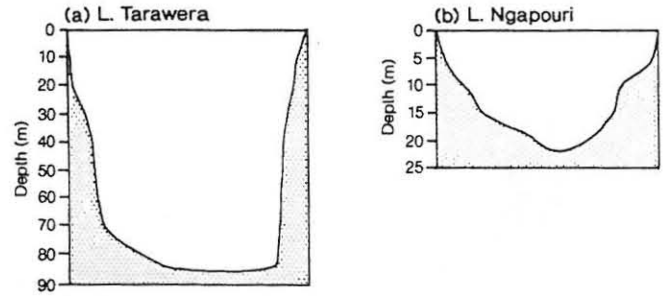


Figure 5.13 Generalised bathymetry of (a) Lake Tarawera, showing its near-vertical sides and flat-bottom, and (b) Lake Ngapouri, showing its funnel shape (after Irwin, 1968).

11.14). The 1886 AD eruption of Mt Tarawera was previously said to have blocked the outlet of the lake (Tarawera River), causing the lake level to rise about 12 m (Healy, 1975a; Lowe and Green, 1987a). However, R. F. Keam (pers comm, 1987) believes that the outlet was not blocked to this extent and that any changes in lake level were much less (Cole, 1970, implied a rise of < 1.0 m).

Lake Okareka was dammed by lavas associated with the Te Rere eruptive episode (about 21 000 years ago), Lakes Tikitapu (Blue) and Rotokakahi (Green) were both dammed by lavas of the Rotorua eruptive episode (about 13 000 years ago), and Lake Rotoma, lying in a small collapse caldera developed much earlier, is dammed by lavas associated with the Rotoma eruptive episode (about 8500 years ago) (Figure 5.10); Froggatt and Lowe, 1990; Lowe and Green, 1987a; Nairn, 1989; Nelson, 1983). The basin bathymetry has been modified by the extrusion of other young rhyolite domes near the centre of the lake. The main part of Lake Rerewhakaaitu originated much more recently by damming by pyroclastic flows resulting from the Kaharoa eruptive episode (about 700 years ago) (Cole, 1970). Awaatua Bay on the western shore of the lake is a small explosion crater about 10 000 years old (Nairn, 1989).

Smaller, subcircular lakes in the Rotorua area occupy explosion craters, and generally have funnel-shaped basins (eg, Figure 5.13). Such lakes include Lakes Rotokawau (see Figure 11.27), Rotongata, and Rotoatua, which are maars formed by basaltic eruptions about 3500 years ago (Froggatt and Lowe, 1990). They lie at the intersection of faults. Small crater lakes, originating from hydrothermal eruptions, are common and

include Lakes Okaro, Ngapouri (Opouri), Ngahewa, and Orotu, and were probably formed at the same time as the Kaharoa eruptive episode (ie, about 700 years ago). A crater lake also occurs on the summit of the andesite–dacite Mt Edgecumbe (Putauaki), the main cone of which formed between about 5500 and 3500 years ago (date based on tephrochronology; Nairn and Wood, 1987).

The youngest lake in the Rotorua area is Lake Rotomahana which formed after the 10 June, 1886 AD Tarawera eruption (Figure 5.14). Previously, two shallow lakes, Rotomahana and Rotomakariri, were situated where the modern lake now occurs,

Figure 5.14 The Rotomahana Basin, photographed from near the summit of Mt Tarawera, a few weeks after its shattering formation during the 10 June 1886 eruption. The Tarawera Rift is evident in the foreground. Present-day Lake Rotomahana is shown in Figure 5.15. The photo was taken in late July or early August, 1886, probably by either F M B Muir or A H Burton (Lowe and Green, 1987a). (Burton Brothers, National Museum of New Zealand, Wellington)

Figure 5.15 A view to the southwest of present-day Lake Rotomahana, photographed from a position similar to that for Figure 5.14. The lake is now the third-deepest lake in the North Island (112 m). (R M Briggs)

but were destroyed during the phreatomagmatic and hydrothermal explosions that produced the present basin. Lake Rotomahana, now one of the North Island's deepest lakes (Figure 5.15), took many years to fill, with the maximum level not being reached until the 1930s (Grange, 1937; R F Keam, pers comm, 1987). In the associated Waimangu thermal area to the southwest of Lake Rotomahana, several small lakes, including two with hot water, lie in craters produced during and following the 1886 eruption.

LAKES IN THE TAUPO AREA

Lake Taupo lies within a complex of caldera and fault structures comprising the so-called 'inverse' rhyolitic Taupo volcano (Figures 5.16 and 5.17). Inverse volcanoes are concave with the 'flanks' sloping gently *inwards* towards the vent locations (Walker, 1984) rather than forming the steep convex cones characteristic of andesite strato-volcanoes (eg, Mt Taranaki) or rhyolite domes (eg, Mt Tarawera). This inverted form, also shown by the Rotorua volcano in Figure 5.11, arises largely because eruptions from rhyolitic volcanoes of this sort are typically so powerful that accumulation of erupted material near the vent is insufficient to counteract the caldera collapse due to magma withdrawal, and because the later effusion of steep-sided domes is comparatively minor. The Taupo volcano slopes inwards at 1–2°, becomes slightly steeper in places and is cut by faults around much of the lake margin. The 'base' of the volcano lies in the lake near the Horomatangi Reefs about 170 m above sea level, and is the lowest point for about 40 km in any direction. The volcano rim, about 50 km in diameter, lies at 600–700 m altitude on the north and northeast sides, thus giving a total relief of about 400–500 m (Houghton and Wilson, 1986).

The Taupo volcano has a long and complex history which reflects the interactions between regional, tectonically-related subsidence and local, volcanically-induced collapse (Wilson, 1986). Its history can be divided into two major periods: (1) the eruption of the Whakamaru-group ignimbrites; and (2) the more recent period comprising a succession of explosive eruptions in the past 50 000 years (Houghton and Wilson, 1986; Wilson, 1986). The Whakamaru-group ignimbrites were previously considered to have been erupted from calderas in Lake Taupo, specifically Western Bay. However, Wilson *et al* (1986) indicate that these ignimbrites were instead probably erupted from the large Whakamaru Caldera postulated to underlie the Maroa area to the north of the lake (Figure 5.10, Inset), and so were not directly involved in the formation of the lake basin. Much of the lake owes its form instead to a series of powerful eruptions, mostly from within the lake basin, in the last 50 000 years, particularly since about 22 000 years ago.

From about 50 000 to 22 000 years ago, five explosive eruptions occurred from vents within the lake basin, ejecting the equivalent of about 10 km^3 of magma. About 22 000 years ago, the enormous Kawakawa eruptive episode took place in the northern part of the lake basin (Figure 5.17) (possibly in the vicinity of the Whangamata Basin), and ejected the equivalent of at least 155 km^3 of magma. The final phase of this eruption culminated in catastrophic caldera collapse to form the main structure of the northern part of the modern lake basin (Figure 5.16); Houghton and Wilson, 1986; Wilson *et al*, 1986). From 10 000 to about 2100 years ago, at least eight explosive eruptions, evacuating about 20 km^3 of magma in total, occurred from north to south along the eastern side of the lake basin, although this part of the lake may also have been shaped by contemporaneous or earlier tectonic downfaulting (Northey, 1983). Several submerged rhyolite domes, and Acacia Bay dome near Taupo, are probably related to some of these eruptions (Figure 5.16; Froggatt, 1981a,b; Froggatt and Solloway, 1986).

The most recent eruption was the dramatic Taupo Tephra eruptive episode about 1850 years ago, the largest eruption from the lake since the Kawakawa eruption. It ejected the equivalent of 35 km^3 or more of magma. The eruption was centred on the Waitahanui Basin-Horomatangi Reefs (Figure 5.16), and consisted of several closely-spaced phases, culminating with an exceptionally powerful and intense ultraplinian eruption (Figure 5.18; Wilson and Walker, 1985).

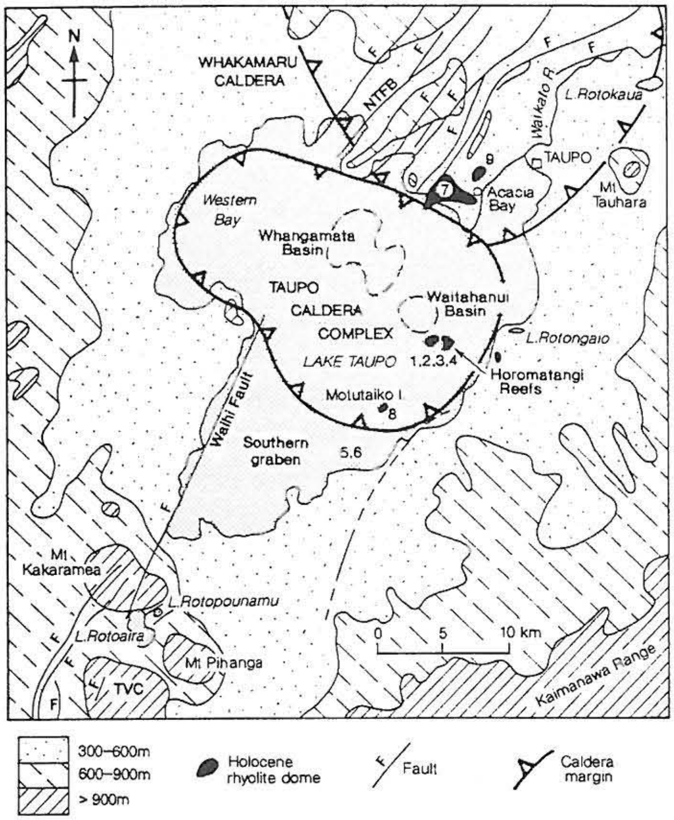
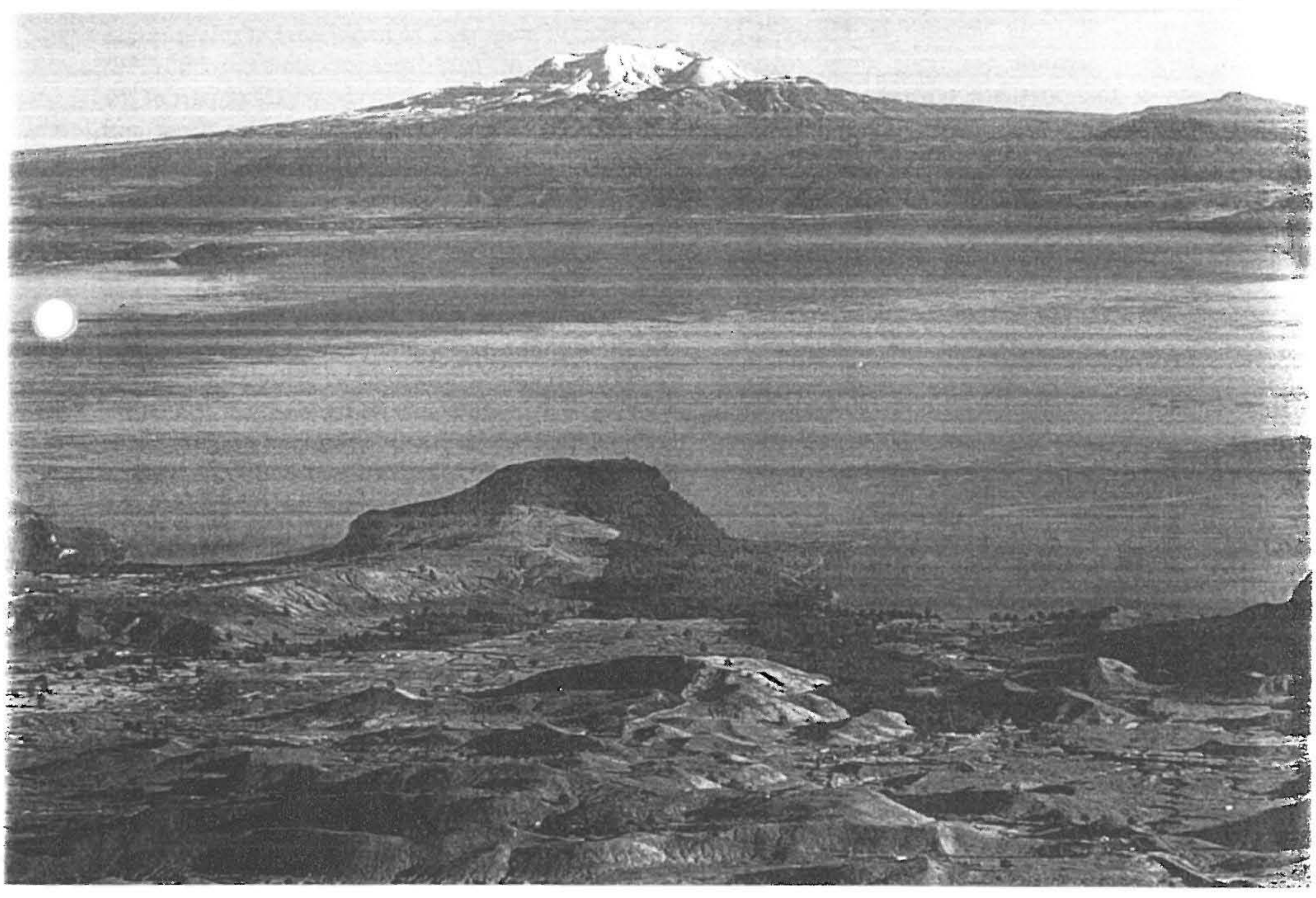


Figure 5.16 Broad structure and topography of the inverse Taupo Volcano with Lake Taupo and the associated Taupo Caldera lying within it. Whakamaru Caldera is postulated to lie to the north (Wilson *et al*, 1986). Numbers mark approximate source vent areas for named Holocene rhyolitic eruptives (after Froggatt, 1982): 1, Taupo; 2, Mapara; 3, Whakaipo; 4, Waimihia; 5, Hinemaiaia; 6, Motutere; 7, Opepe; 8, Poronui; 9, Karapiti (see also chapter 2). Based on Wilson and Walker (1985), Wilson *et al* (1984, 1986), and Houghton *et al* (1987). NTFB, Northern Taupo Fault Belt; TVC, Tongariro Volcanic Centre. Present lake level is 357 m above sea level.

Figure 5.17 A southward-looking view of Lake Taupo, New Zealand's largest lake. This tranquil scene belies the lake's explosive history within one of the world's most powerful rhyolite volcanoes. The northern part of the lake is formed in the Taupo Caldera Complex; in the south it lies in the Southern Graben bounded to the west by the Waihi Fault (see Figure 5.16). The embayed land in the foreground comprises mainly rhyolite lava domes and flows and pyroclastic deposits of the North Taupo Fault Belt; in the background are the snow-capped andesitic stratovolcanoes of Tongariro Volcanic Centre. (D L Homer, DSIR Geology and Geophysics)



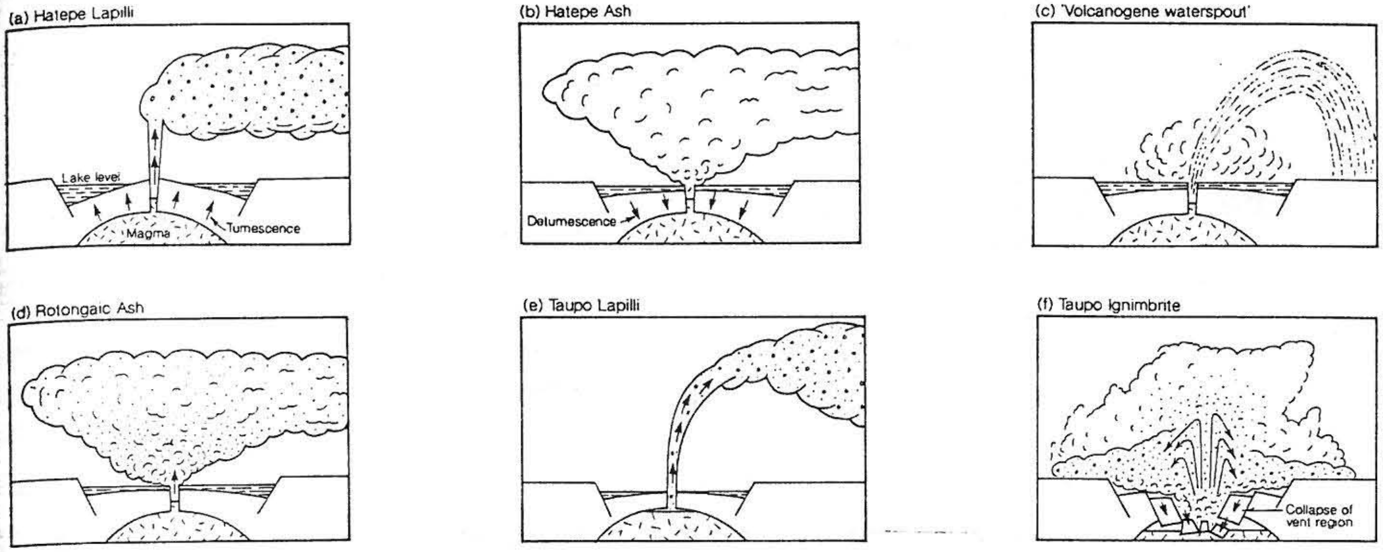


Figure 5.18 The various phases of the Taupo Tephra eruption about 1850 years ago in the vicinity of the Horomatangi Reefs-Waitahanui Basin area. The eruptive episode resulted in the emptying and subsequent refilling of Lake Taupo. After Cas and Wright (1987), based on Wilson and Walker (1985).

This phase (Figure 5.18e) led to major caldera collapse and ignimbrite generation (Figure 5.18f) in the vent region within the northeasten part of the large caldera formed by the Kawakawa eruption. The Horomatangi Reefs are probably domes extruded soon after this phase.

Multiple radiocarbon dates on material associated with the Taupo Tephra have a mean age of 1850 ± 10 years BP, equivalent to a calendar date in the range AD 138–230 (Froggatt and Lowe, 1990). A previous calendar date of AD 186, based on ancient Roman and Chinese accounts of unusual atmospheric effects supposedly related to the eruption of fine ash from the Taupo Tephra into the stratosphere, has now been discounted because of errors in the translations and other difficulties (Froggatt and Lowe, 1990). Recent studies of trees buried by the Taupo Ignimbrite at Pureora (Clarkson *et al*, 1988; Palmer *et al*, 1988) suggest that the eruption occurred in late summer or early autumn in the period AD 165–190 (perhaps AD 177), matching the range suggested from radiocarbon dating.

The lake was essentially emptied during the Taupo Tephra eruption generating what has been described as a 'volcanogene waterspout' (Figure 5.18c). A buried wave-cut bench 110 m below the lake's surface marks an initial lake level soon after the eruption. The lake probably took about 10–20 years to refill, reaching about 30 m above its present level to form several wave-cut benches (Grange, 1937; Wilson *et al*, 1986). The lake fell to its modern level when the exit channel, the Waikato River, was re-established (Healy, 1975a).

The northern bays of Lake Taupo (Figure 5.17) represent a horst and graben fault complex (the North Taupo Fault Belt). Some of these faults have moved since the Taupo eruption and have displacements of up to several tens of metres, although the timing of most of the movement is uncertain (Wilson *et al*, 1986).

In summary, much of the northern part of Lake Taupo occupies a complex caldera created largely during the Kawakawa and Taupo eruptive episodes; the southern part of the lake infills a dominantly tectonic graben structure (Northey, 1983; Wilson, 1986).

Other volcanic lakes in the Taupo area include Lake Rotokaua, north of Lake Taupo, which occupies a hydrothermal explosion crater that was formed possibly about 5000 years ago (Cole and Nairn, 1975). The lake basin was considerably larger before the Taupo Tephra eruption and is now largely infilled with deposits from this eruption. Lake Rotoaira lies in a fault-bound basin between the Tongariro and Pihanga volcanoes dammed by lava flows from Tongariro. It is floored by Taupo Tephra, indicating that it was formed earlier than 1850 years ago. A number of smaller explosion craters also occur (Lowe and Green, 1987a): on Pihanga, Lake Rotopounamu was formed in the last 10 000 years; on Tongariro, Blue Lake (16 m deep) and the Tama Lakes were formed about 10 000 years ago, and the Emerald Lakes, occupying phreatic explosion craters, were formed following recent eruptions associated with Red Crater and are less than 1850 years old (Hackett and Houghton, 1986); near Ohakune, the Rangatau Lakes are younger than 10 000 years; and on Ruapehu, Crater Lake (see Figure 11.20), first developed about 1800–2000 years ago (Palmer, 1991), occupies an active vent and so the lake basin is being continually modified by volcanic activity. An important eruption occurred in 1945 when an island of molten lava grew to displace the lake entirely. It was then destroyed by explosion and collapse to leave a pit about 300 m deep, which eventually filled with water. In 1965, the lake had a maximum depth of 298 m but by 1970 it was only 80 m deep at its maximum, probably because of lava moving upwards under the lake. The shape of the lake thus changed from that of a champagne glass to a bowl (Hurst and Dibble, 1981). The lake contains hot water (the maximum surface temperature recorded is 60°C) and was about 60 m deep in 1983.

LAKES IN AUCKLAND AND NORTHLAND

These lakes have formed largely as a result of basaltic volcanism. In Auckland, many lakes were formed in craters or dammed against lava flows, but most of these have since been drained, commonly through crater-wall breaching, leaving diatomite or swampy deposits (Searle, 1981). Western Springs and Lake Waiatarua (Lake St John) are examples of lava-dammed lakes. Western Springs abuts lava flows from Mt Eden and is younger than 20 000–30 000 years, while Lake Waiatarua was formed by lava flows from Mt Wellington about 9000 years ago (Newnham and Lowe, 1991). Other lakes in Auckland lie in basins originating through explosive phreatomagmatic eruptions. Most of these craters, including Panmure Basin, Tank Farm, and Onepoto (eg, see Figure 5.19), have since been breached and flooded by the sea but Lake Pupuke, which is probably aged 40 000 years or older, remains as a 64 m-deep maar on the North Shore (Figure 5.19).

In Northland, Lakes Omapere and Owhareiti both seem to have formed from damming by lava flows. Preliminary analyses on sediments in cores from Lake Omapere suggest that a lake first formed in the basin roughly 100 000 years ago. Since then there have been a series of transitory lakes, most of which were probably very similar to the modern shallow and weedy lake, but some may have been bigger (Harper, 1988). Radiocarbon dates (Hogg *et al*, 1987) indicate that the modern lake refilled about 1000 years ago, and this may have been because of blockage of drainage caused by erosion in the catchment, coincident with Polynesian habitation and deforestation in New Zealand (eg, Newnham *et al*, 1989).

OTHER AREAS

Two lakes, Aroaraotamahine and Te Paritu, occur on Mayor Island. Both are effectively dammed like moats against the wall of the Mayor Island caldera by a young lava dome extruded into the centre of the caldera, possibly only a few thousand years ago (Houghton and Wilson, 1986). On Mt Taranaki, Lake Dive was formed when drainage was dammed by extrusion of the Northern Beehive lava dome about 3000 years ago or earlier (see Figure 12.5A).

Dune Lakes

Dune lakes are associated with wind-blown sand deposits, and are particularly common in coastal regions. A considerable variety of dune-lake types has been recognised and classified (Bayly and Williams, 1973; Hutchinson, 1957; Lowe and Green, 1987a; Timms, 1982). However, these all appear to be variations of two major types: 'barrage lakes' and 'deflation lakes'.

1 Dune barrage lakes. There are two main types: dammed-valley and dune-contact. 'Dammed-

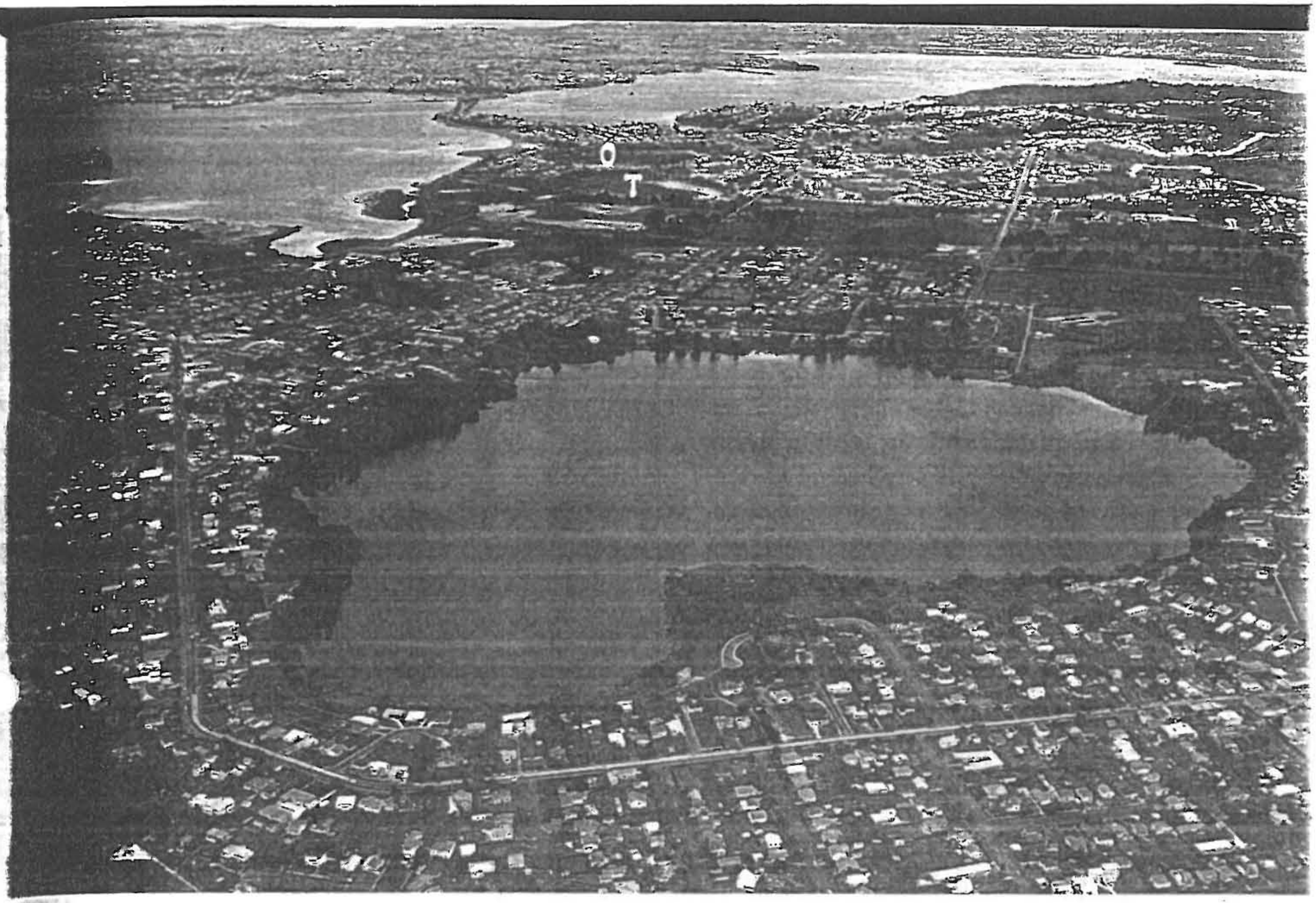


Figure 5.19 Lake Pupuke, a 64 m-deep basaltic maar in North Shore City (Takapuna), viewed from the north. The breached Tank Farm (T) and Onepoto (O) explosion craters, which formerly held lakes, are visible to the south. (Whites Aviation, Auckland)

valley lakes' are formed when dunes block a valley draining towards the coast; they vary considerably in shape but are often roughly triangular-shaped with the deepest regions close to the dune dam, or with one or more long narrow arms up-valley from the dune. The sides of such lakes are typically steep and the catchments have a relatively high relief. 'Dune-contact lakes' occur in depressions between two or more dunes, or between dune belts. Shapes vary, but are typically elongated and relatively shallow, and catchments are usually of low relief.

2 Deflation lakes. These occupy hollows produced by excavation by wind erosion, or uneven accretion, or both, and are almost always associated with dune sand deposits. Two major types may be recognised, depending on the presence or absence of an impervious layer beneath the lake basin: 'perched dune lakes' and 'watertable-window lakes' (Timms, 1982). In perched dune lakes the water, derived largely from rainfall, is held by an aquiclude that may be formed in various ways (eg, organic accumulation, iron pan formation). In watertable-window lakes there is no impermeable layer and a lake forms when the groundwater levels are high enough to be exposed in the deflation basin; the lake levels thus fluctuate according to the watertable level (the basins hence provide a 'window' to the watertable).

Wind-blown sand deposits are abundant on the west coast of the North Island, hence most dune lakes occur there. Others are found on the east coast of the North Island, at a few locations in the South Island, and on the Chatham Island (eg, Lakes Pateriki and Kairae, and many others — see Hay *et al*, 1970, and Wright, 1959).

The sand dune systems of the west coast of the North Island occur in broad strips up to 50 km wide that consist of belts of dunes usually subparallel to the coastline (eg, Figure 5.20). The belts generally increase in age inland from unstable active frontal coastal dunes that are less than about 150 years old, to moderately weathered, fixed Pleistocene dunes that rise to elevations of 100–200 m. The mechanisms and timing of dune mobilisation and stabilisation are complex (see chapter 7). In the last 6500 years or so dune belts formed roughly synchronously along the west coast of the North Island but it is difficult to correlate episodes of dune-building phases between and within different areas because dune deposits may be time transgressive (Bussell, 1988; Shepherd, 1987). Many dune lakes occur at boundaries between dune belts (eg, Figure 5.20) and thus their minimum ages may be determined from the ages of the dunes forming the dams. Most are probably less than about 6500 years old with the exception of those in the Kawhia-Aotea Harbours area where they (eg, Lake Taharoa) appear to be older than about 50 000 years. Such older lakes indicate that lakes have probably always been a feature of 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 examples are thus likely to overlie older lake deposits.

Most of the dune lakes have not been studied in enough detail to enable their mode of origin to be categorised, except in some obvious cases, although both barrage and deflation types are probably represented (Cunningham *et al*, 1953). Major groupings occur on the west coast between North Câpe and Kawhia Harbour (Figure 5.1). Those on the Aupouri and Karikari Peninsulas are not well known; near Dargaville, Lakes Kai-iwi and Taharoa are probably dammed-valley barrage lakes of mid-Holocene age; on the North Kaipara Peninsula most (eg, Lakes Humuhumu and Waingata) are likely to be dune-contact barrage lakes of late Holocene age, being impounded by active dunes. The South Kaipara Peninsula lakes include two dammed-valley barrage lakes, Ototoa and Kuwakatai: Ototoa, dammed by Dune Belt 1, is about 3000–4500 years old while Kuwakatai, dammed by Dune Belt 2, is about 2000–3000 years old. A string of smaller lakes south of these (eg, Lake Kereta) are probably dune-contact lakes aged 1500–2000 years old, being dammed by Dune Belt 3 (Figure 5.20; Schofield, 1975). Those north and south of the mouth of the Manukau Harbour (including Lake Pokorua and Parkinson's Lagoon) are mid-Holocene or younger and are mainly dune-contact lakes; Wainamu is a dammed-valley lake. Near Aotea and Kawhia Harbours, a number of lakes

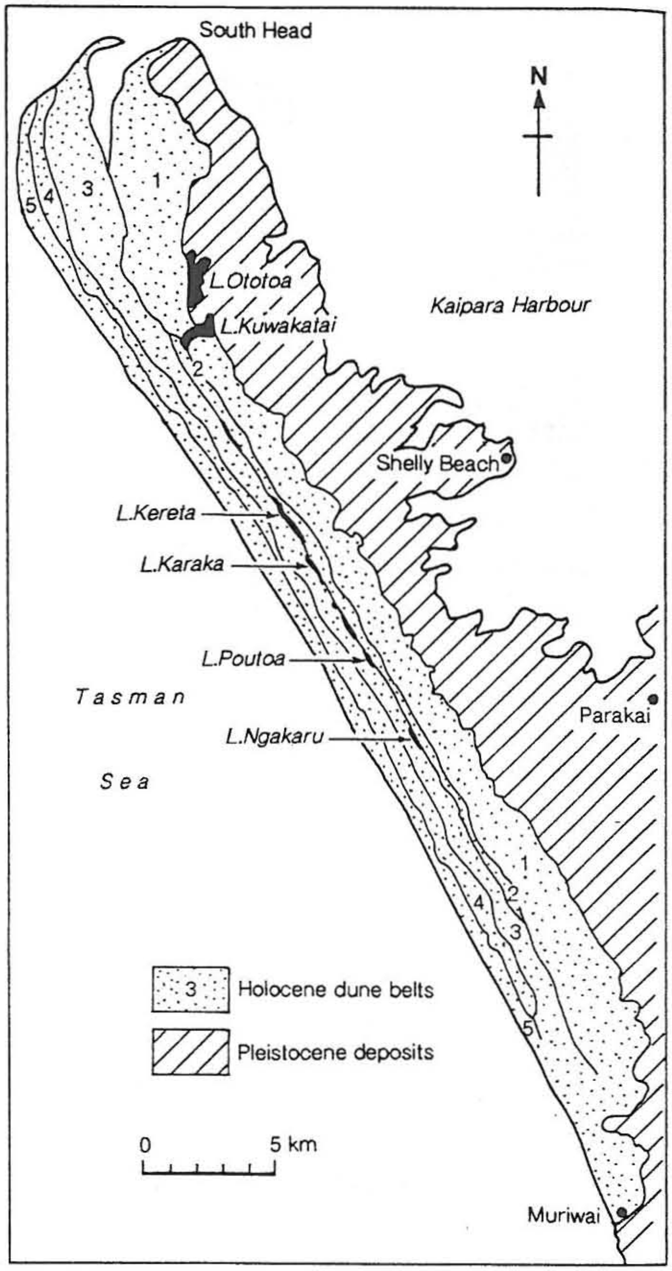


Figure 5.20 Dune lakes aligned along the contacts of belts of Holocene dunes, South Kaipara Peninsula. The dune belts have ages estimated as follows (years BP): 1, 3000–4500; 2, 2000–3000; 3, 1500–2000; 4, 300–1500; 5, <300. After Schofield (1975).

including Parangi, Taharoa, and Harihari are dammed-valley lakes impounded by the Te Akeake Sands which were deposited between about 50 000–88 000 years ago; the sands are capped by the Rotoehu Ash (Pain, 1976; Stokes, 1987).

A second major group of dune lakes occurs along the Manawatu-Horowhenua coast (Figure 5.1) associated generally with three major dune belts (the Foxton, Motuiti, and Waitarere Sand Phases: Cowie, 1963; see chapter 13). The ages of the dune belts are broadly known but there is some uncertainty about the ages of the dunes locally because a period spanning several thousand years may have elapsed between the initiation of a dune accumulation phase and its final stabilisation (Shepherd, 1987; Shepherd and Price, 1990). Dune movements probably occurred episodically at different localities many times in the past (Bussell, 1988). Deposits of the Foxton Dune Phase, originally considered to have formed about 2000–4000 years ago, may range from 1600–6000 years in age (Shepherd, 1987; Shepherd and Price, 1990) and so lakes impounded by these deposits (eg, Lake Horowhenua, a dune barrage lake near Levin; Figure 5.21) are likely to have formed in this period. However, recently obtained radiocarbon dates on sediments in a core from nearby Lake Papaitonga show that this lake was formed about 8000–8500 years ago, the earliest recorded age associated with the Foxton Dune Phase deposition. Lakes dammed by the Motuiti Sand Phase are likely to be about 600–1850 years old and include Lakes Alice and Omanuka. The youngest group was dammed by the Waitarere Sand Phase and these lakes are about 350–550

Figure 5.21 Lake Horowhenua, a shallow (2 m) dune lake near the town of Levin. Several smaller dune lakes lie tucked in against the extensive hairpin-shaped longitudinal sand dunes in the foreground. The Tararua Range to the east forms the background to the photograph. (D L Homer, DSIR Geology and Geophysics)

years old; they include both dammed-valley (eg, Lake Heaton) and dune-contact lakes (eg, Lakes Pukepuke and Pothole).

Further north on the Wanganui coast near Waverley, Lake Waiau was formed by dune movement blocking the Waiau Stream before about 3500 years ago (Bussell, 1988).

Other smaller areas of dune lakes are shown in Figure 5.1. All of these are likely to be of Holocene age. For example, Slipper, Spectacle, and Tomarata Lakes near Mangawhai were probably formed some time before the development of the Mangawhai Spit dunefield 700 years ago (Enright and Anderson, 1988). In South Westland, the Tawharekiri Lakes originated within the last 8000 years or so, possibly about 3000–5000 years ago.

The dune lakes are small, all being $< 5\ km^2$ in area; most ($> 80\%$) are $< 0.5\ km^2$ (Lowe and Green, 1987a). They are also generally shallow, the deepest lakes being on the west coast of the North Island (eg, Lake Waikere has a maximum depth of 30 m; Lake Ototoa 29 m; and Lake Taharoa, North Kaipara Peninsula, 37 m). Some lakes have regular or flattish basins (eg, Lake Rotokawau, Karikari Peninsula). Others have irregular basins with channels and sills demarcating small basins which tend to lie in the same direction along the major axes of the lakes (Cunningham *et al.* 1953; Irwin, 1972).

Riverine Lakes

Fluvial processes can result in the formation of a variety of riverine (or fluviatile) lakes, the two most important types being 'lateral lakes' and 'oxbow lakes'. Lateral lakes form when a large river aggrades faster than its lateral tributaries, thus resulting in the formation of lateral levees which may then dam the tributary drainage. Lateral lakes are very common in the valleys of larger rivers. Oxbow lakes, also known as billabongs, are formed by the cutting off of meander loops and in other abandoned river channels. A third type is the 'alluvial-fan dammed lake' which is usually associated with modified glacial lakes, as described previously.

The lower reaches and floodplains of most New Zealand rivers have been the sites of extensive and active aggradation since the last glaciation (see chapter 4). Riverine lakes are widespread in these areas and are the second most abundant lake type in New Zealand (Table 5.2). Apart from Lakes Wairarapa and Waikare, they are mostly small ($< 0.5\ km^2$), generally flat bottomed and shallow, usually being only a few metres deep (1–9 m).

Lateral lakes include Lake Wairarapa, which was a large coastal embayment (estuary) until between 2200–4000 years ago when the Ruamahanga River built an alluvial dam across the seaward end of the embayment, converting it into a body of freshwater. This development possibly accompanied or followed warping and tilting in the region, and the basin occupies a shallow structural sag with its western margin abutting the Wairarapa Fault (Palmer *et al*, 1989; Figure 16.6). In the historical past, Lake Wairarapa was seasonally more extensive than at present. Previously, the lake outlet reached the sea via Lake Onoke through a bar-gap which would close during summer (see Figure 5.26). In autumn and early winter water levels would rise 4 m, flooding the entire area so that Lakes Onoke and Wairarapa joined and the Ruamahanga River backed up to Martinborough. Levels dropped in late winter when the impounded water breached the barrier-bar again (Palmer, 1984). Extensive lacustrine deposits occur in the vicinity of Lakes Waiararapa and Onoke, and some of these are probably Last Interglacial in age when a large lake apparently occupied much of the Wairarapa Valley (Palmer *et al*, 1989).

Many of the lakes in the Waikato region are lateral lakes. Most were formed between 15 000–17 000 years ago during the final stages of aggradation of the Hinuera Formation by the ancestral Waikato River (Lowe and Green, 1987a). The Hinuera Formation comprises volcanogenic alluvium deposited in the form of a large low-angle fan built up by braided channels migrating across its surface (see chapter 10). Lakes were formed between levees adjacent to the channels or where levees blocked drainage in embayments in hills protruding through the Hinuera Formation (eg, Figures 10.9 and 10.12). Several short-spaced episodes of alluvial deposition are evident in the formation of some of the lake basins (eg, Lakes

Figure 5.22 Lake Te Koutu (middle right of photo), a shallow riverine lake in Cambridge, was formed about 1850 years ago when Taupo Pumice Alluvium carried by the Waikato River (left) was deposited in the Karapiro Stream valley (lower part of photo), thereby blocking drainage. (M J Selby)

Maratoto, Rotokaraka, and Rotongata). Subsequently, many of these lakes have been further deepened by the growth of adjacent peat bogs and so the lakes in their present form are of complex origin. The detailed developmental history of one of these lakes, Lake Maratoto, is shown in Figure 10.11 (Green and Lowe, 1985).

Other lateral lakes in the Waikato area were formed more recently by the deposition of the Taupo Pumice Alluvium adjacent to the modern Waikato River about 1850 years ago, and include Lakes Te Koutu (Figure 5.22), Waahi, Hakanoa, Waikare, and Whangape.

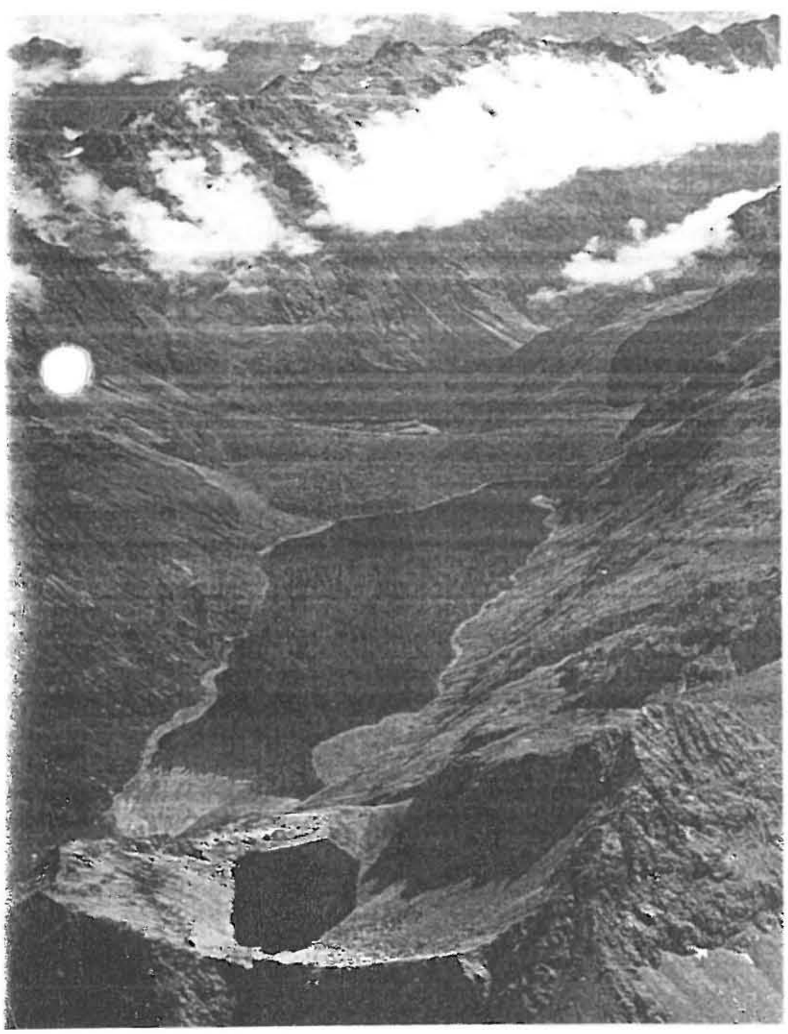
Oxbow lakes are common in the Kaihu, Manawatu, Taieri, Mataura, Ruamahanga, Wairau, and the lower reaches of the Clutha River valleys (Figure 5.1; Cotton, 1958). All these lakes are likely to be of late Holocene age because they lie on recently active floodplains and hence may be subject to frequent flooding and sediment infilling. Small lakes on the Rangitaiki Plains (Bay of Plenty) associated with the Rangitaiki and Tarawera Rivers were probably formed within the past 1850 and 700 years, respectively (Nairn and Beanland, 1989).

Although most alluvial-fan dammed lakes have been classed as glacial because the basins originated chiefly as a consequence of glacial (or early-post-glacial) activity, some may well prove to be entirely fluvial in origin.

Landslide Lakes

Landslide lakes form by blockage of drainage in valleys by debris from landslides. Typically, most landslides that form lakes are rock avalanches or rock falls that originate from the failure of all or part of a mountainside, and fall rapidly from the ridge crests into the valleys, piling up against the far valley walls (Adams, 1981a; Costa and Schuster, 1988; Whitehouse, 1983; see chapter 3). The resultant hummocky deposits, usually lobate where not confined by local topography, may resemble glacial moraines but differ from them by being asymmetrical about the valley axis, by the presence of swash features and debris on valley sides, and the source scar above the deposit (Whitehouse and Griffiths, 1983). In addition, they contrast with moraines in containing a jumble of large blocks and open crevices and may also include abundant remains of trees and other vegetation that once grew on the pre-landslide slopes. Landslides are always associated with areas of steep terrain. The main triggering mechanism is seismic activity (earthquakes), but intense rainfall and snowmelt are also known causes (Costa and Schuster, 1988; Whitehouse and Griffiths, 1983).

Figure 5.23 Lake Constance, a landslide lake at 1300 m altitude lying within a once-glaciated valley near the headwaters of the west branch of the Sabine Valley. The lake is impounded by a huge rockfall from the Franklin Ridge (marked by the scar at right), and is being infilled by fan deposits and a small delta at its head. The small tarn in the foreground is a cirque lake. Another lake (Blue Lake) lies on the valley floor just beyond the landslide dam, and is fed by springs draining underground from Lake Constance. (D L Homer, DSIR Geology and Geophysics)



Landslide lakes are generally short-lived because they may rapidly infill with sediment eroded from the catchment, or the river filling the lake may wash out or overtop the landslide dam. Often the breaching results from headward stream erosion starting at the toe of the dam. On this basis, Adams (1981a) has distinguished two types of landslide lakes: 'temporary lakes' on large rivers that are soon destroyed, and 'permanent lakes' on tributaries that may remain for thousands of years. The permanence of the lakes depends mainly on the size of the landslide and the size of the river dammed, and even very large landslides are unlikely to dam the largest rivers permanently.

In New Zealand, the active tectonic environment produces both the rugged terrain and frequent seismic activity needed for landslides, and regions of high rainfall generally coincide with areas of fast uplift and high relief (chapter 3). Landslide lakes are thus relatively abundant, and are the fifth largest group in New Zealand (Table 5.2), occurring in catchments comprising mainly sedimentary rocks in eastern North Island (Figure 5.1), near Wanganui, the northwestern part of the South Island, and in the central and southern glacial region. Furthermore, the numbers of landslide lakes have been underestimated in the past because the origins of some have been ascribed to other processes, particularly glacial or fluvial activity. They include Lake Christabel, Lake Constance (Figure 5.23), Lake Lochnagar, and Green Lake in the South Island.

Numerous temporary landslide lakes were formed when landslides caused by the 1929 Buller earthquake dammed the major rivers in the region. 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 rock fall in the Buller earthquake blocked the Matakitaki River to form Mud Lake, which filled with water in four days, but which was later destroyed by a combination of draining and sediment infilling (Adams, 1981a). Lake Ngatapa (Te Hoe) was formed during the 1931 Napier earthquake in Hawke Bay when a landslide dammed a tributary of the Mohaka

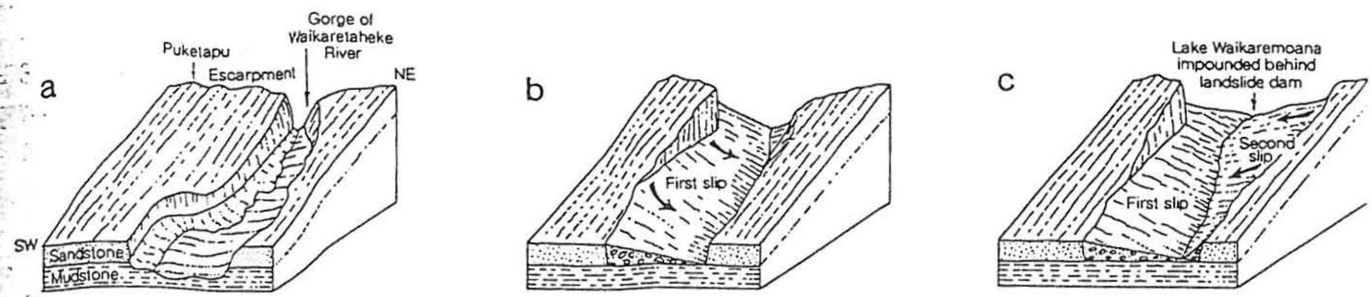


Figure 5.24 Sketches showing the impounding of Lake Waikaremoana by a landsliding episode on its southeastern margins: (a) the pre-lake Waikaretaheke River passes through the tilted escarpment in a gorge; (b) part of the escarpment southwest of the river slides into the gorge, forcing the river to the northeast; (c) a possible second landslide falls from the northeast, diverting the river slightly southwestward. After Marshall (1926).

River. This lake, 2 km long and 25 m deep, appeared to be permanent but washed out in a flood in 1938.

About 70 per cent of the known New Zealand landslide lakes can be categorised as 'permanent' because they either formed in pre-historic times or have an expected life of hundreds of years. The largest and best known permanent landslide lake in New Zealand is Lake Waikaremoana in the Urewera National Park. It is dammed by two large landslides: the first was the largest and fell from the southwest side of the Waikaretaheke River; the second, much smaller, fell from the northeast side (Figure 5.24). The part of the dam formed by the first slide appears almost impervious while the part formed by the second slide consists of larger rocks with numerous crevices through which water has escaped (Marshall, 1926). A dozen springs were known prior to the development of hydroelectric power stations on the Waikaretaheke River below the landslide dam. During construction for the power development, rock-fill was dropped from barges to seal these leakages.

The age of the sliding events is uncertain. Radiocarbon ages of about 2200 years on standing dead trees exposed at low lake level show that the lake was formed at or before this time, but the presence of Waimihia Tephra (3300 years old) on the landslide debris indicates that the major landslide movement took place before about 3300 years ago (C G Vucetich, pers comm, 1991). The lake probably took about 10 years to fill (Marshall, 1926), and has the V-sided basin and dendritic shoreline typical of most landslide lakes occupying river valleys (Irwin, 1975b; Main, 1976). Lake Waikaremoana is the deepest lake in the North Island (248 m) and the seventh deepest in New Zealand (Table 5.3).

Other lakes in the vicinity of Lake Waikaremoana and in the Hawke's Bay region that were evidently formed by landslides include Lakes Kiriopakae, Rotongaio, Tutira, and the Tiniroto Lakes. Lake Tutira and the Tiniroto Lakes were both formed by landslides of mudstones about 6500 years ago, and the latter have since been largely infilled with muddy organic sediments (Howorth and Ross, 1981; N Trustrum and M Page, pers comm, 1991).

Lake Rotokare, near Eltham in Taranaki, is probably a valley-dammed landslide lake formed before about 1900 years ago. Lake Namunamu, near Wanganui, was probably also formed in this manner.

Permanent landslide lakes occur more frequently in the South Island than in the North Island. Lake Stanley was formed during the 1929 Buller earthquake by a landslide which fell 800 m from the northern slopes of the Snowden Range to dam the upper Stanley River, and with enough force to deposit debris nearly 200 m above river level on the opposite bank. The lake has a maximum depth of about 40 m just upstream from the landslide dam (Figure 5.25). Sediments from other landslides triggered by the 1929 Buller earthquake are presently forming a rapidly-growing delta that is filling the lake.

Lake Matiri is a landslide-dammed lake on the Matiri River north of Murchison. About 15×10^6 m^3 of rock and fine debris fell 600 m from the western slopes of the Bald Knob Range, damming the valley to a depth of about 30 m around 300 years ago. The lake is now only 20 m deep because of subsequent infilling by a delta at the north end of the lake and hence has a predicted total life of less than about 700 years (Figure 5.25; Adams, 1981a). Lake Matiri and seven other small prehistoric landslide lakes in the Buller area are thought to have been formed by a past earthquake because of their proximity and similar characteristics to the lakes formed during the 1929 Buller earthquake (Adams, 1981b).

Lake Christabel, on the uppermost Grey River, is probably landslide-dammed (Figure 5.25). Suggate (1965) considered the barrier to be a glacial moraine, but it lacks the smooth outwash surface that normally extends downstream of young moraines in other parts of the South Island (Adams, 1981a). The barrier contains large angular blocks of schistose greywacke and its permeability seems high. About 80 per cent of the normal flow of the Grey River passes through the barrier, appearing as springs downstream of it. The age of the lake is uncertain. Trees several hundred years old cover the barrier and the amount of sediment in the lake seems more likely to represent about 1000 years of catchment erosion rather than the 10 000 years or so if the lake is of glacial origin (Adams, 1981a).

Lake Chalice, on the Goulter River west of Blenheim, was formed by a 100-m high landslide barrier about 2200 years ago (Figure 5.25). The sides of the lake basin are very steep and slope at 60°. The lake level is about 15 m below the lowest point on the landslide and the lake drains underground through the barrier so that the lake level fluctuates considerably.

In the Southern Alps between Arthur's Pass and Mt Cook, 46 Holocene rock avalanches of indurated sandstone and mudstone, with volumes ranging from 1 million to 500 million m^3, are known and some of these have formed lakes (Whitehouse, 1983; Whitehouse and Griffiths, 1983). Such rock avalanches have also formed lakes in the southwest part of the Southern Alps. Lake Adelaide is formed by a massive granite landslide whereas Green Lake was formed by a gneissic rock avalanche. The latter is the largest known rock avalanche in New Zealand, and has a volume estimated to be 1.4×10^{10} m^3 which is

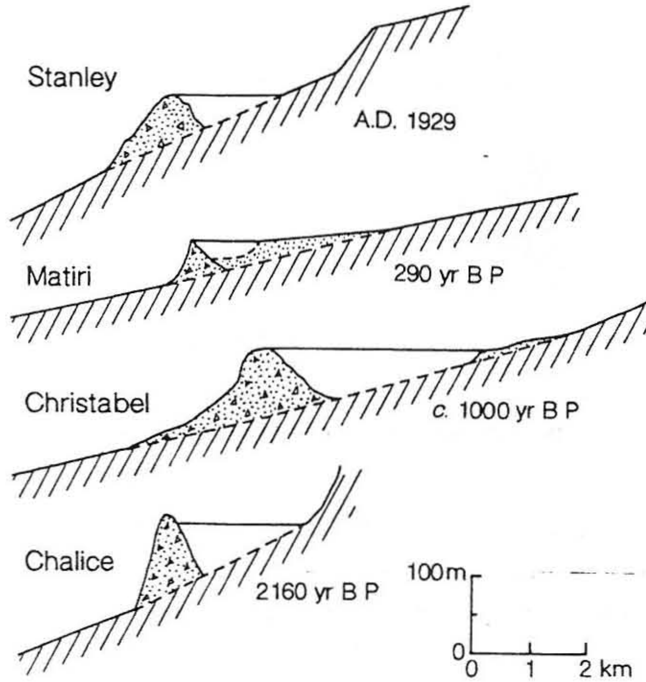


Figure 5.25 River bed cross-sections of four South Island landslide-dammed lakes, based on topographic maps; lake bathymetry is sketched in. Age of lake formation is indicated. After Adams (1981a).

similar to the largest described on earth, the 2×10^{10} m^3 Saidmarreh landslide in Iran (Whitehouse, 1983). Lake Lochnagar is dammed by a 270×10^6 m^3 rock avalanche derived from a 100-m thick slab of schist which slid along a plane of schistosity.

Barrier-Bar Lakes

These lakes form through the enclosure of inlets or embayments or estuaries by barrier-bars or spits. The barriers originate by wave action, often coupled with sea level fluctuations or tectonic movement, and are thought to have formed mainly through marine reworking of alluvial gravels and sands during the Holocene post-glacial transgression. Gravel-pebble (shingle) barriers predominate where there is a large gravel input into the littoral system (see chapter 7). The lakes usually occur adjacent to river mouths near the sea and most therefore lie at low altitudes ($<$ 30 m) on the coastline, as lagoonal features.

In the North Island they are found along the Wellington-Palliser Bay coastline (eg, Lake Onoke, Figure 5.26) and near the Wairoa River near Gisborne (eg, Whakaki Lagoon). In the South Island, where they occur more frequently, barrier-bar lakes predominate on the east coast, particularly Marlborough (eg, Lake Grassmere), Canterbury (eg, Lakes Ellesmere and Forsyth), and Dunedin (eg, Wainono and Tomahawk Lagoons). Others are in Westland (eg, Lake Windemere) and on Ruapuke Island in Foveaux Strait. Te Whanga Lagoon and various other lakes on Chatham Island probably originated through barrier-bar impoundments (Allan, 1928; Hay *et al*, 1970). Several barrier-bar lakes occur within larger lakes, including Onewhero Lagoon, which is separated from the eastern shore of Lake Rotoma by a wave-formed shingle and sand spit, and Lake Rotongaio on the eastern shore of Lake Taupo.

All the barrier-bar lakes are probably of Holocene age. The few studies that have been done indicate that they generally attained their present form within the last 6500 years or so when sea level reached its present position (Gibb, 1986). Whakaki Lagoon formed since about 4000 years ago by the closing of an estuary by a sandy barrier (Ota *et al*, 1989). Lakes Kohangatera and Kohangapiripiri, near Wellington, originated as drowned inlets through sea level rise and down-tilting before about 6500 years ago. The inlets were cut off by shingle spits then by gravel barriers widened by successive uplift since about 3100 years ago (Figure 5.27; Stevens, 1973). Lake Onoke, impounded against alluvium deposited by the Ruamahanga River, was probably formed around the same time (4000–5000 years ago); nearby Lake Pounui (Figure 5.26) formed about 2500 years ago or earlier (G M Turner, pers comm, 1991). Lakes Grassmere and Ellesmere, on the Marlborough and Canterbury coasts respectively, developed in several stages: an initial phase of spit growth enclosing a marine bay followed by extensive shoreline reorientation by erosion and accretion since about 6000–7000 years ago (Armon, 1974; Figure 7.9). Lake Forsyth, near Lake Ellesmere, has apparently been permanently impounded since early European settlement (by barrier 4, Birdlings Flat; Figure 7.9), previously being open to the sea. Thus the present lake may

Figure 5.26 Lake Onoke, a barrier-bar lake fed by the Ruamahanga River on the south Wairarapa coast adjacent to Palliser Bay. Lake Pounui is also visible in the low hills in the background, which rise to form the Rimutaka Range. (M R Balks)

be only 150 years old. If the older barriers (1–3) previously extended right across the inlet of the basin, then the lake may have existed in earlier periods until the barriers were breached. Gage (1980) suggested an age of about 1000 years for Lake Forsyth's cut off.

Most barrier-bar lakes are small ($< 0.5\ km^2$) but two are relatively large: Lake Ellesmere ($182\ km^2$) and Te Whanga Lagoon ($160\ km^2$). They are typically shallow (1–5 m) and D-shaped or oval, but may have irregular outlines on the inland margins. Sizes and depths can vary considerably because of fluctuations of lake level through tides, and changes in outlet configuration. The coastal barrier-bar lakes are commonly brackish (New Zealand's table salt is produced by evaporation from Lake Grassmere). Some may remain landlocked until they fill to certain levels when channels are cut through the barriers and waters drain out to sea (eg, Te Whanga Lagoon breaches naturally in approximately seven-year cycles), although levels may be controlled artificially (eg, Hughes *et al*, 1974).

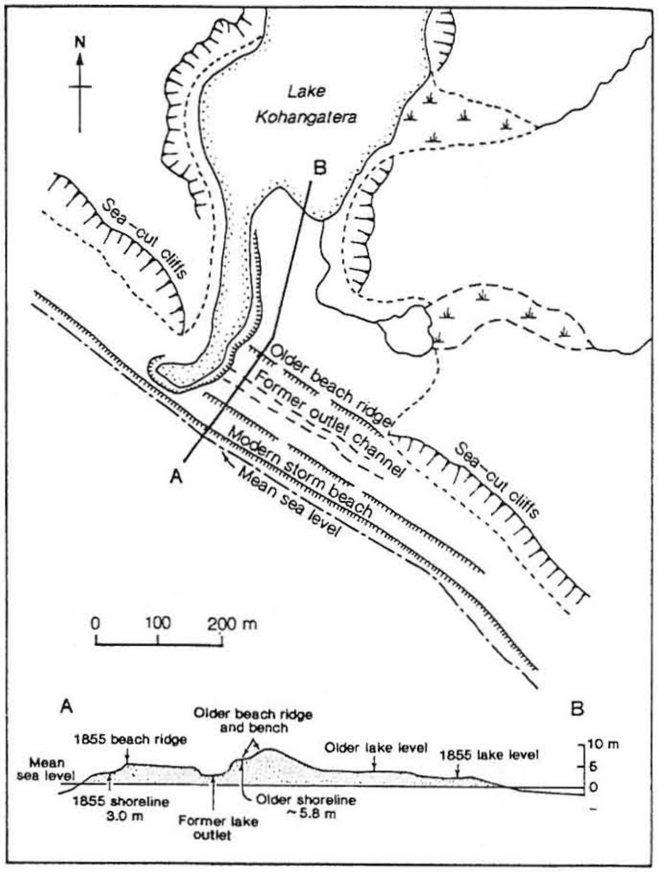


Figure 5.27 Map and cross-section of beach ridges on gravel barrier-bars impounding Lake Kohangatera, Pencarrow Head, Wellington. The 'Older beach ridge', uplifted about 600 years ago, was formed after about 3100 years ago. An earlier lake may have existed in the area because gravel beach ridges aged about 3100–6500 years occur close by on this coast. After Stevens (1973).

Tectonic Lakes

Tectonic lake basins, formed wholly by movements of the earth's crust, are very uncommon in New Zealand, but various lakes modified by displacement of the ground surface are better known. Most of these occur in the seismically-active Hawke's Bay region in the North Island (eg, Lakes Hatuma, Poukawa, Runanga, Horseshoe, and Roto-o-kiwi) (Lowe and Green, 1987a). All are modified to some extent by alluvium or peat deposits (eg, as described for Lake Poukawa by Harper *et al*, 1986). Lake Wairarapa has in the past been regarded as one of New Zealand's few tectonic lakes (Cotton, 1958), but it is now known to be a riverine lake (see above). A series of small ponds near Waimangu, in the Rotorua district, all < 1 ha in area, have formed where the slopes of the Earthquake Flat Crater (see Figure 11.11) have been cut by a fault downthrown on the upslope side. All the little erosion valleys thus truncated have tectonically-produced ponds at the fault (R F Keam, pers comm, 1987).

Several South Island lake basins, including Lakes Ellery, Kaurapataka, Sumner, and Brunner, are thought to have been influenced by faulting. In Dismal Valley near Lake Sumner, for example, vertical and horizontal movement on the active Kakapo Fault has resulted in the formation of a small, unnamed tectonic lake, referred to as a fault-pond by Yang (1991). Thus, while definitive tectonic lakes are few, many lakes in New Zealand have been formed as an indirect consequence of the country's pervasive tectonism (eg, those formed by earthquake-induced landslides and most volcanic lakes).

Solution Lakes

Solution lakes — sometimes called karst lakes — occur in karst terrains in which carbonate rocks, mainly limestones and marbles, have been dissolved by percolating natural waters to produce a characteristic landscape (see chapter 8). In such areas, most solution occurs by rainwater falling on and descending through the carbonate rocks to form corrosion hollows. As well, subsurface streams enlarge cavities which may collapse to produce depressions. These basins may be of various sizes and shapes: dolines are funnel-shaped; uvala are formed when adjacent dolines fuse; and poljes are large karstic depressions. Any of these may fill with water to form a lake, which may be ephemeral if the water is periodically lost when drainage through cracks and joints in the underlying rock material is greater than input by precipitation.

Solution lakes are rare in New Zealand, reflecting the relatively uncommon occurrence of karst landscapes. The largest solution lake is Lake Disappear (see Figure 8.3), which periodically occupies a polje associated with Tertiary carbonate rocks in the western King Country area near Aotea Harbour. The polje is flooded after heavy rainfall when the flood inflow is greater than the drainage can discharge. The lake fills to a depth of about 15 m. Other small lakes in dolines (eg, Lake Koraha) occur in the limestone country south of Kawhia Harbour and north of Raglan Harbour.

Small, perhaps periodic, solution lakes probably occur in limestone or marble terrains in the Hawke's Bay, Wairarapa, Nelson, and South Canterbury regions (eg, see chapter 19). For example, roughly circular snow-filled dolines in the Mt Owen region presumably form small lakes after snowmelt (chapter 8). Lake Marakapia and Lake Rotoparaoa, and several others, on Chatham Island are thought to have formed initially as doline solution lakes but may have been subsequently modified by sand-dune barriers (Allan, 1928; Hay *et al*, 1970).

Peat Lakes

Although many lakes have been secondarily affected by peat development, there are few known New Zealand examples of lake basins that have resulted primarily from organic accumulations. Such peat lakes, also known as phytogenic lakes (Lowe and Green, 1987a), may sometimes form when rapidly-growing vegetation impedes drainage, in a similar way to the formation of lateral lakes by alluvial deposition. Grange *et al* (1939) suggested that some of the lakes around the peat bogs in the Waikato region may have formed in this way, but this has not been substantiated (Green and Lowe, 1985). Peat growth has contributed to the later stages of development of these lakes, however (chapter 10).

Some of the dozen or so small lakes in peat bogs on the Chatham Islands, such as Lake Rotokawau, may have formed in hollows in the peat surface resulting from peat fires (Allan, 1928; Wright, 1959). These fires have been known to burn for many years, producing holes about 3 m deep.

Ponds and small lakes may also develop in hollows on peat surfaces formed by spatial variation in rates of peat deposition. Such variations may be caused when differences in subsurface relief affect the supply of soligenous water (mineralised groundwater) and thus the development of ombrotrophic, or peaty, conditions (Boatman *et al*, 1981). This process may be operative in New Zealand, and two examples are the lakelets within the Kaipo Lagoon peat bog and other montane bogs near Lakes Waikareiti and Waikaremoana (Lowe and Hogg, 1986), and the many pools within the Lagoon Saddle mire near Mt Bruce, Canterbury (Dobson, 1975). In both cases, the pools are less than about 10 000 years old; those in the Kaipo Lagoon are possibly about 5000 years old. Lakelets and small pools also occur frequently in the Kopouatai peat dome in the Hauraki region, and in the Ahukawakawa Swamp in Taranaki, and many of these could probably be classed as peat lakes.

Artificial Lakes

Most of these lakes date from this century, many since the 1950s. In general, large artificially-dammed lakes provide storage for hydroelectric power generation, and many small artificially-dammed lakes, including farm ponds, are reservoirs for urban and rural water supplies or irrigation systems. Other types include those formed by flooding of worked-out open cast mines,

Figure 5.28 Lake Karapiro, viewed from the north, is an artificial hydroelectric lake on the Waikato River formed in 1947. It has a maximum depth of about 31 m. (M J Selby)

quarries, or deep holes excavated by hydraulic elevating in the pursuit of gold (eg, Blue Lake, St Bathans, Central Otago). Small lakes may be formed by excavation of low-lying swampy ground for recreational or aesthetic purposes (eg, Knighton, Oranga, and Chapel Lakes on the University of Waikato Campus, Hamilton).

The major North Island hydroelectric lakes occur on the Waikato River, draining Lake Taupo (eg, Figure 5.28); in the South Island, most occur on the Waitaki and Clutha River systems (Figure 5.1). Lake Benmore, on the upper Waitaki River, was formed in 1965 and is New Zealand's largest artificially-dammed lake (74 km^2) and has a maximum depth of 91 m. 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 longest (46 km) artificially-dammed lake in New Zealand, with a maximum depth of 58 m.

SUMMARY

New Zealand has a great variety of lake types within a small land area as a result of its active tectonic regime, its recent volcanicity, and the effects of repeated Pleistocene glaciations, which together have produced an earthquake-prone, generally rugged and youthful landscape conducive to the formation of lake basins. The broadly localised distribution of geological processes has resulted in geographical groupings of ten main lake types into distinct lake districts: for example, 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 riverine lakes are prevalent on the floodplains on the major river river systems of both islands. The North Island has a predominance of small dune and riverine lakes and of volcanic lakes in the central volcanic region. The South Island has a predominance of glacial lakes, many at high altitudes, and of riverine lakes. Other lakes occur in small numbers throughout the country and include landslide, barrier-bar, tectonic, solution, peat, and artificial lakes. Many lakes have multiple origins and have been affected by more than one geomorphological process following their formation and so have complex developmental histories.

Most of the lakes are young, and many are aged between about 5000 and 10 000 years. Some are older, such as the Waikato riverine lakes which are about 16 000 years old; and a few of the dune and volcanic lakes which are about 50 000 years or older. Younger lakes include several volcanic lakes, probably all of the landslide lakes, and many of the riverine, dune, and barrier-bar lakes. Almost all the artificial lakes have been formed this century.

The bathymetry and morphology of the lake basins are generally well known, all the major lakes having been surveyed in detail.

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