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Beach Changes on Low Energy Lake Shorelines, Lakes Manapouri and Te Anau, New Zealand[1]

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ABSTRACT

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Sand and gravel beaches around the shores of Lakes Manapouri and Te Anau, New Zealand generally respond to fluctuations in wave energy and still water level in a similar manner to large lake and ocean beaches. However, there are some important differences. Short fetch lengths produce a narrow range of wave conditions and shore normal changes to the beach profile are minimal in order to maintain an equilibrium form. Largest beach changes are induced by fluctuations in lake level and alongshore transport of sediment in closed beach compartments. Low energy levels limit the size of sediment in transport and much of the shoreline is protected by lag pavement beaches, the size of the lag and winnowed sediment being controlled by maximum wave conditions. Frequent calms allow all types of beach morphology to be drowned or stranded by lake level fluctuations.

ADDITIONAL INDEX WORDS: *Lake, sand/gravel/lag beaches, shorelines, water level changes, waves.*

INTRODUCTION

Detailed studies of limnic beaches have concentrated on large lakes, and in particular the Laurentian Great Lakes of North America. The size of these lakes means that their associated beach processes often have closer affinities to low energy ocean shorelines than smaller lakes. comparisons have been drawn between ocean and large limnic systems in beach morphology (DAVIS *et al.*, 1972), in sediment distribution (MOTHERSILL, 1970), in changes of beach morphology in response to storms (FOX and DAVIS, 1973) and in response to water level fluctuations (DUBOIS, 1975, 1976). In contrast there are few detailed studies of beach systems on small lakes where levels of wave energy are much lower. This paper investigates morphologic changes in beaches around Lakes Manapouri and Te Anau, New Zealand, and examines functional relationships between these changes and controlling processes. Differences and similarities with ocean and large lake systems are highlighted.

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PHYSICAL SETTING

Lakes Manapouri and Te Anau fill glacially overdeepened basins, dammed at their eastern boundaries by outwash terminal morains (Figure 1). Long narrow, formerly glaciated arms extend west and north into the Fiordland mountains. Te Anau is 61 km long, 10 km maximum width and covers an area of 352 km^2. Manapouri is 29 km long and extends over 153 km^2. The bathymetry of the lakes reflects their origin. Both are deep with maximum depths of 444 m in Manapouri and 417 m in Te Anau (IRWIN, 1969, 1971), producing cryptodepressions of 267 m and 215 m respectively. Lake levels on both lakes fluctuate directly in response to precipitation and runoff, rises of 0.8 m in a week are not uncommon. Manapouri has a range of 4.8 m and Te Anau 3.9 m. Since 1969 lake levels have been semi-controlled but the range has not been reduced.

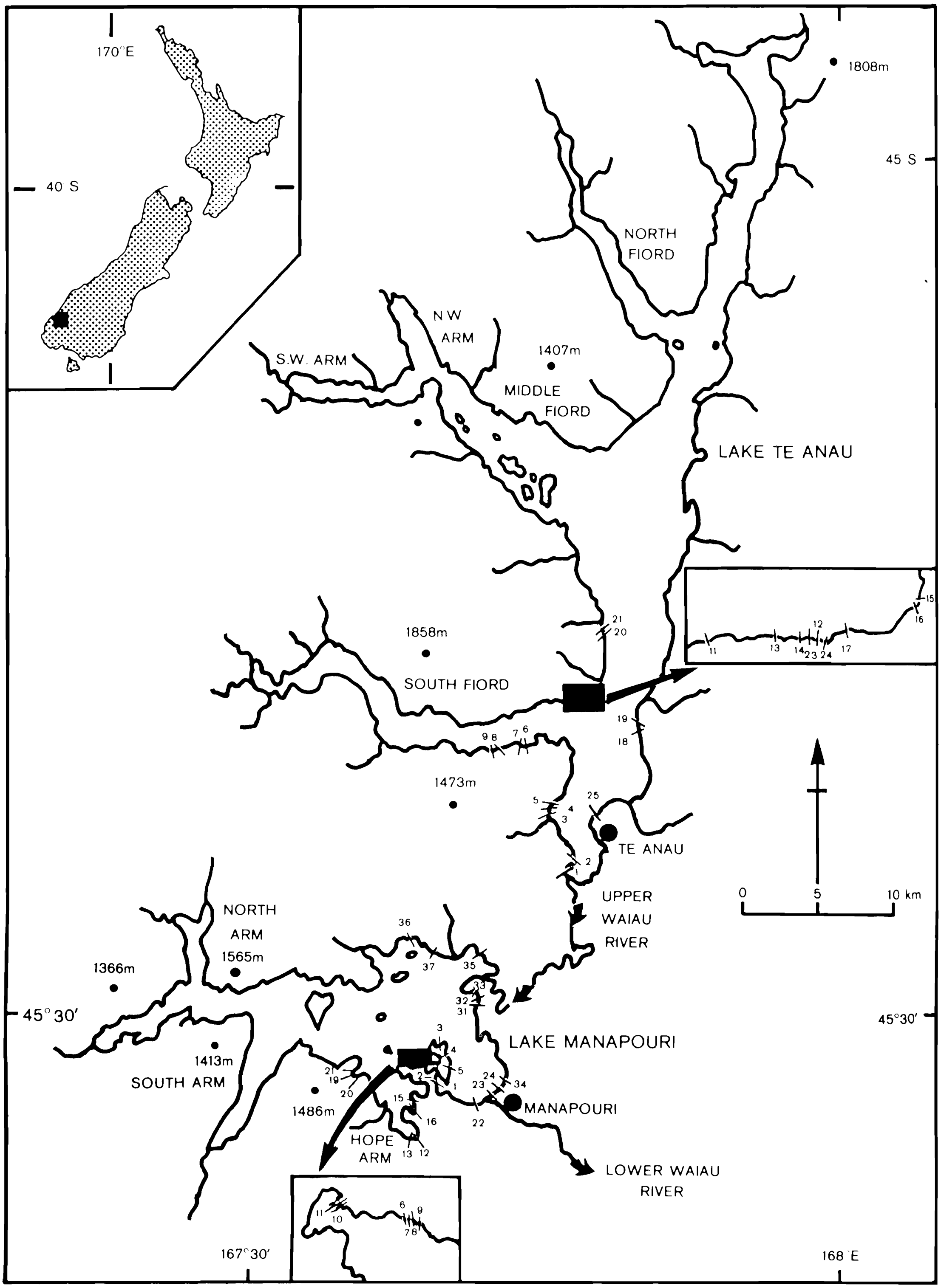
170°E
40°S
1808m
45°S
NORTH FIORD
N.W. ARM
S.W. ARM
1407m
MIDDLE FIORD
LAKE TE ANAU
1858m
SOUTH FIORD
1473m
TE ANAU
UPPER WAIAU RIVER
0 5 10 km
NORTH ARM
1565m
1366m
45°30'
1413m
SOUTH ARM
1486m
LAKE MANAPOURI
HOPE ARM
MANAPOURI
LOWER WAIAU RIVER
167°30'
168°E

Figure 1. (Facing page) Beach profile locations, Lakes Manapouri and Te Anau. The numbers correspond to profiles in subsequent figures.

In the north and west of both lakes the shoreline remains substantially unaltered since deglaciation, with Paleozoic gneisses and granites and Tertiary mudstones and sandstones forming steep cliffs (WOOD, 1962, 1966). Beaches have formed where rivers have brought sediment to the littoral zone and in re-entrants where the nearshore relief is not too steep allowing pocket beaches to form from sediment sources in the immediate hinterland. Along the south and east shores beaches are more plentiful in the unconsolidated moraines. Sediment ranging from fine sand to boulders is supplied to the littoral zones from fluvial and moraine sources. The elongated shape of both lakes funnels wind and waves down the long axis of the lakes such that processes of littoral drift lead to local alongshore transport of sediment and size selective sorting. As a result sand, gravel and mixed sand-gravel beaches form at the downdrift end of littoral cells and denuded gravel and boulder pavements form at the updrift ends (Figure 2).

Despite the varied origins of the different beaches they all develop a distinctive shelf profile. Beach sediments grade lakeward into fine sand across a gently sloping nearshore shelf. The outer edge of the shelf is marked by a shelf break and a transition to organic-rich muds on a steep offshore slope (PICKRILL, 1978). The shelf is an equilibrium form developed in response to wind waves. As the exposure to wave activity increases the nearshore shelf widens, the depth of the shelf break increases and the slope decreases (PICKRILL, 1978). Subsequent research has shown similar equilibrium shelves have formed on the sheltered shores of the Straits of Georgia and Juan de Fuca, British Columbia (PICKRILL, 1980, 1983). Close parallels have been drawn between the formation of these shelves on fetch-limited shores and the development of progradational shelves on continental margins, suggesting there is a continuum of shelf morphologies between the high energy continental margins and low energy sheltered coasts.

METHODS

Thirty six beach profiles were established around Lake Manapouri and 23 around Te Anau (Figure 1).

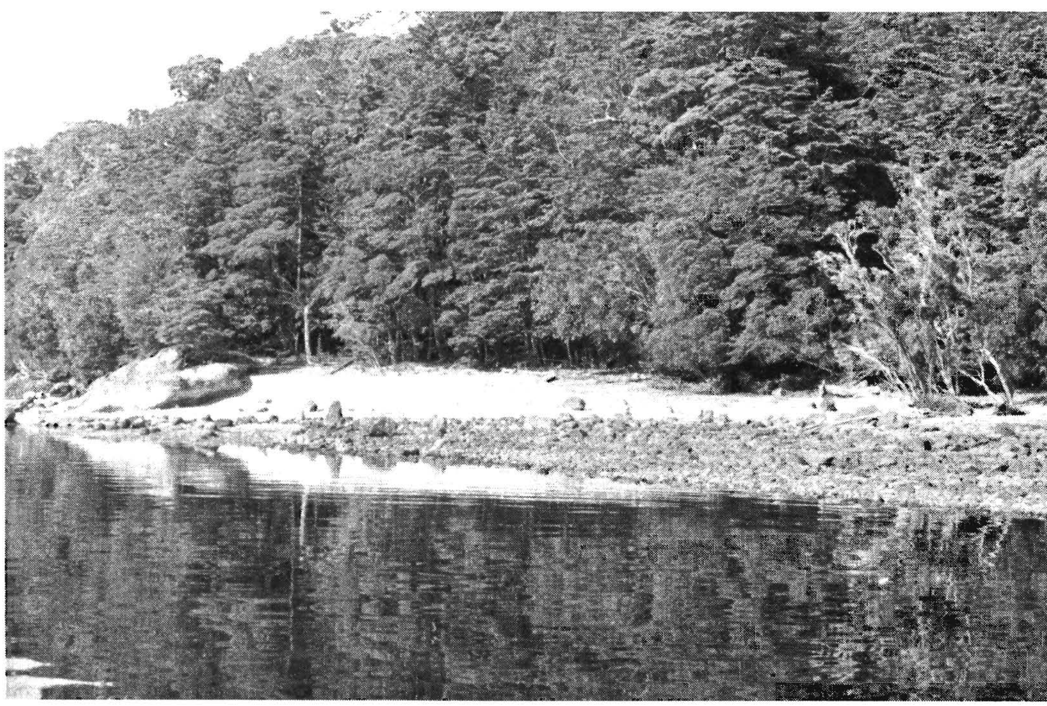

Figure 2. Moraine shoreline on Lake Te Anau, near profile 20 (Figure 1). A denuded gravel and boulder pavement beach has formed on the exposed shoreline, whereas a small sand beach has formed against a downdrift re-entrant.

Six bi-monthly surveys of the profiles were made with a quick-set level and staff. In the summer selected beaches were surveyed more frequently, including a daily survey of one beach for 75 days. In all 441 beach profiles were surveyed.

RESULTS

Pavement Beaches

Pavement beaches are an erosional surface with a thin veneer of pebbles, cobbles and boulders, often just one layer thick, embeded in a matrix of poorly sorted moraine. Pavement profiles are wide and flat (Figure 3). However finer interstial sediments, winnowed from the underlying matrix, may accumulate in low storm ridges in response to wave activity during periods of stable lake level (Figure 3). More mobile sediment fractions are transported alongshore in these storm ridges to feed sand and gravel beaches at the downdrift end of the littoral cell.

Figure 3. Gravel storm ridge formed on a lag pavement surface (profile M31) in response to a prolonged period of static lake levels. The staff is 1.7 m long.

Wave generation is limited by fetch, wind speed and duration. On small lakes with short fetch lengths, fully arisen wave systems develop quickly and, if wind conditions are assumed uniform over the body of the lake, then fetch can be used as an index of wave energy which almost increases linearly with effective fetch (U.S. ARMY COASTAL ENGINEERING CENTER, 1977, p.3.29) for any given wind speed (PICKRILL, 1983, Figure 5). On pavement beaches around Lakes Manapouri and Te Anau the size of the sediment increases as a function of the effective fetch (Figure 4A). It is inferred that the maximum size of sediment capable of being winnowed out of the pavement increases with the potential energy within the wave climate. Sediment tracer experiments confirm that wave energies are insufficient to move the coarser sediment of the moraine which is left as a lag deposit (PICKRILL, 1976). Similarly sediment winnowed from the pavement and deposited in the storm ridges increases in size with increasing wave energy (Figure 4B). A comparison of the texture of the lag and winnowed sediments shows the two overlap (Figure 4B), suggesting the finer interstitial

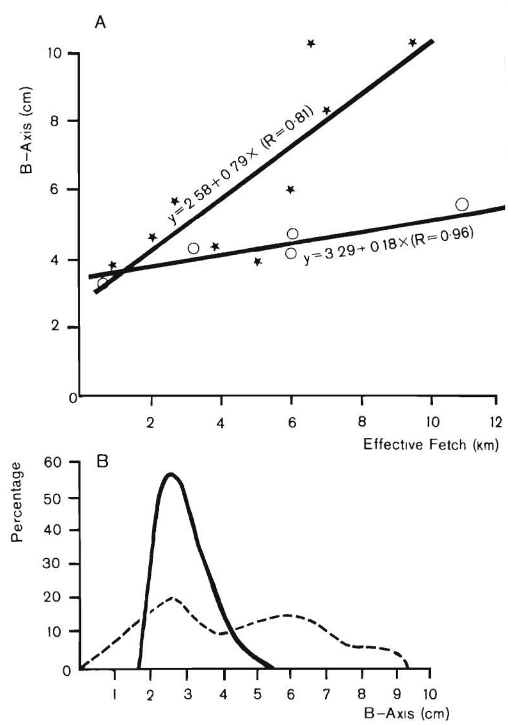

Figure 4. (A) Size of sediment on pavement beaches from the suface (x) and gravel ridges (o) plotted as a function of effective fetch length. B, or second longest axis of particles measured in the field with callipers. (B) Textural comparison of lag (----) and ridge (——) sediments.

sediment is winnowed from the poorly sorted lag pavement to form the well sorted gravel storm ridges and that the lag surface is being actively reworked.

Repeated profile surveys show the pavements to be stable. The gravel storm ridges commonly remain unaffected by lake level fluctuations during calm or low energy conditions. For instance on Lake Manapouri water levels rose 0.9 m between two of the bimonthly surveys. Initially this rise was slow and steady until the 5 days preceding the second survey when the level rose 0.37 m. A well developed storm ridge present during the first survey moved 5 m landward in response to the initial slow rise in water level. The subsequent rapid rise in levels submerged the ridge under 0.4 m of water and left it structurally unchanged (Figure 5A). Such submergences are common, particularly on Manapouri, where short term lake level fluctuations are frequent, and the lake is calm for long periods (PICKRILL, 1978). Still stands of lake level lead to large scale ridge growth, whereas fluctuating lake levels during high energy conditions produces thin lenses of sediment across the pavement that may be drowned or stranded by any subsequent changes in water level or reworked into storm ridges during periods of still stand.

Gravel and Mixed Sand Gravel Beaches Two Types of Profile Form

On beaches with coarser sediments profiles are steep and dominated by swash backwash processes. Waves break close to the beach face, the swash erodes incised profiles with steep slopes at the swash limit, sometimes forming near-vertical faces (Figure 5C).

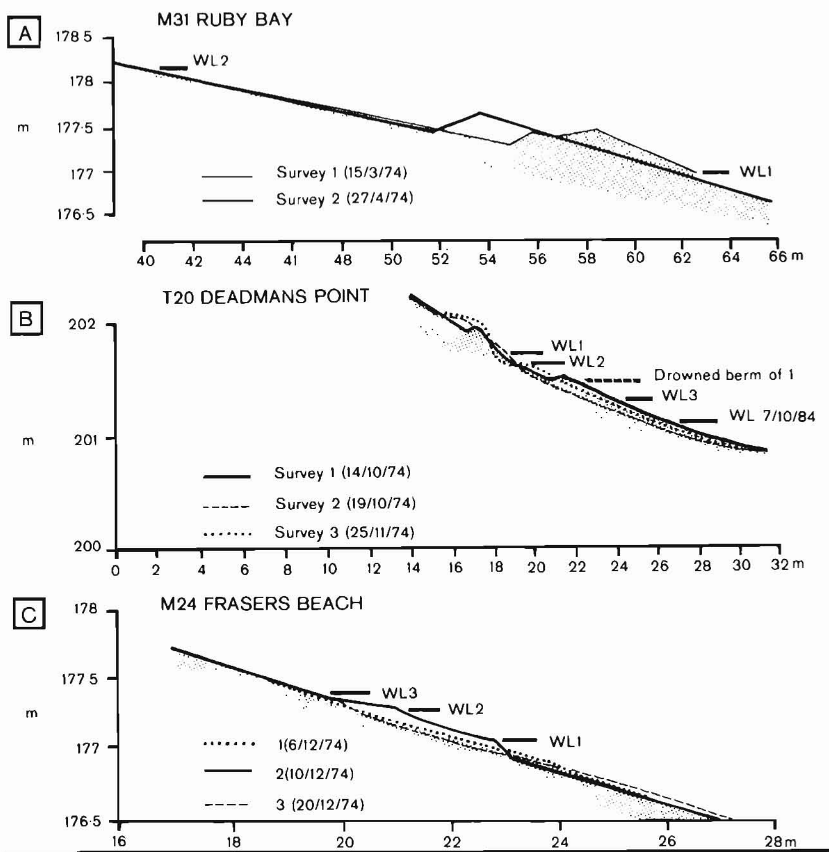

Figure 5. Typical profile changes on pavement and mixed sand gravel beaches. (a) On a pavement beach illustrating the landward movement and submergence of a gravel ridge in response to a rise in water level (WL). (b) On a gently sloping mixed sand gravel beach illustrating the drowning and subsequent landward movement of a beach ridge in response to rising water levels. Note that for illustrative purposes the scales vary between profiles. (c) On a steep mixed sand gravel beach.

Where the beach has a higher content of sand and fine gravel the profile has a lower slope and depositional ridges form across the foreshore in response to fluctuating lake levels (Figure 5B). Shore normal sorting concentrates the coarser sediment in the ridges and the finer fraction in the treads. As on pavement beaches drowned ridges are produced by rapid rises in water level during calm conditions. For instance a large gravel ridge formed in response to 5 weeks of steady water levels (Figure 5B). A 60 cm water level rise over 5 days flooded the ridge but left it unaltered, it remained another 9 days before finally being eroded and replaced by another higher up the beach. Falling lake levels during calm conditions leave these ridges stranded beyond the reach of breaking waves.

Sand Beaches

Profile morphology and changes are best illustrated by the 75 days of diurnal monitoring at Slipway Beach, Lake Manapouri. The fine sand beach has a ridge and runnel morphology which forms at different elevations up the foreshore in response to changing lake levels (Figure 6). The ridge is an accretionary feature elevated above the general beach surface with a steeper face than the rest of the foreshore. The ridge crest is normally horizontal or sloping gently landward into a runnel (Figure 6). Overwash sediment and water is recirculated back to the beach face from the runnel via outlet channels spaced regularly along the beach. During low energy conditions surging breakers form a wave break step, just below water level. As wave energy increases waves begin to spill, the step is eliminated and replaced by a concave profile and a surf zone up to 5 m wide.

The limited effective fetch (5.3 km) places rigid constraints on both the range and maximum size of waves arriving at the beach. Significant wave height and period never exceeded 30 cm and 3 sec. during the survey period. As a result changes in beach morphology during periods of still water level are very small. The accretionary ridge runnel topography is built up to maximum storm elevations from sediments

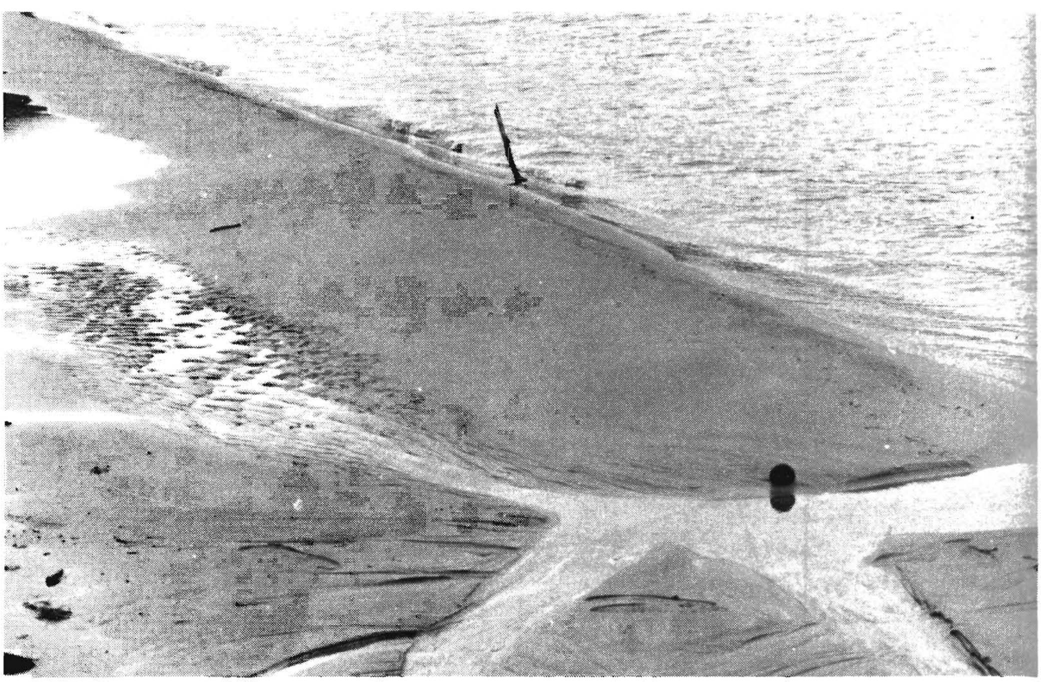

Figure 6. Ridge and runnel morphology at Slipway Beach (M34). The ridge is in an accretionary stage in response to rising lake levels. Note the sharply defined ridge crest and near horizontal runnel. Overwash material is spread in a thin veneer and deposited on this backface. Water and sediment is recirculated back into the lake via a series of runnels and outlet channels as in the foreground of the photograph. The diameter of the lens cap is 5 cm.

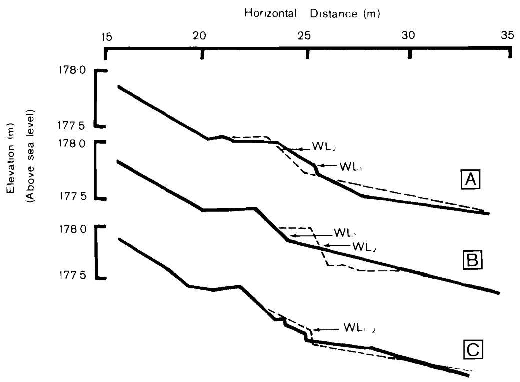

Figure 7. Changes (---) in beach morphology on a fine sand beach, Slipway Beach (M34) Lake Manapouri. (A) Over a 4 day period in response to a 0.17 m rise in water level (WL); (B) Over a 4 day period in response to a 0.10 m fall in water level; and (C) Over a 4 day period of static water level.

on the lower foreshore. During periods of lower energy secondary ridges may be built at lower elevations and waves break on a step (Figure 7C). However the step is soon eroded and the ridges welded back to the main ridge with a return to higher energy conditions.

The largest beach changes are induced by fluctuations in lake water level. Beach changes during rising water levels generally conform to those predicted by BRUUN (1962) following a rise in sea level and subsequently confirmed by numerous researches in wave tank experiments (*e.g.* SCHWARTZ, 1967), and in the field (*e.g.* DUBOIS, 1975). The evidence was reviewed by BRUUN (1983) 21 years after his original prediction. Typical profile changes under rising lake levels are illustrated in Figure 7A. SCHWARTZ (1967) summarized the changes in profile form resulting from a rise in sea level, although the Bruun Rule did not take into consideration sediment deposition at the top of the beach following sea level rise (MCLEAN, 1973). Changes at Slipway Beach (Figure 7) confirm Schwartz's Bruun Rule is generally applicable to accretionary profiles and may be summarized as: (1) There is a shoreward displacement of the beach profile relative to fixed geographical co-ordinates., (2) The material eroded from the central beach is equal to the sum of material deposited on the upper beach (swash limit) and nearshore bottom. (3) The rise in elevation of the upper beach resulting from deposition is equal to the rise in sea level. (4) The rise in elevation of the nearshore bottom as a result of deposition is equal to the rise in sea level. (5) The geometry of the final profile is similar to the geometry of the initial profile.

The Bruun Rule was initially put forward as a cause of shore erosion and not as an accretionary theory. However during falling levels on Lake Manapouri the sequence of changes ensuing from a rise in water level is reversed (Figure 7B) except that sediment deposited at the top of the beach is left stranded beyond the reach of wave activity. As a result rising lake levels produce a net lakeward redistribution of sediment and falling levels a net landward movement.

Alongshore Transfers of Sediment

So far the discussion of beach changes has been confined to shore normal exchanges of sediment produced by variations in the elevation at which waves strike the beach and the level of wave energy. However the largest changes in beach morphology are induced by alongshore transport of sediment.

Funneling of winds and waves down the long axes of the lakes generates bidirectional littoral drift systems. The effect littoral drift has on the beach morphology is a function of this local drift regime, the size of the littoral cell, and the boundary conditions limiting the beach compartment. On long beaches (> 0.5 km) with indistinct boundaries large volumes of sediment may pass alongshore through the beach but have negligible effects on the morphology. By contrast on small well defined beach compartments, such as pocket beaches, the finite sediment supply and rigid boundary conditions can produce large changes to the beach profile.

The effects of alongshore sediment movement on the beach is well illustrated by sweep zone envelopes. On both high energy and low energy beaches with a narrow wave approach window and minimal or unidirectional drift the sweep zones are narrow (Figure 8A). The area contained by the envelopes is no larger than necessary to accommodate shore normal transfers of sediment in response to variations in wave energy and fluctuating lake levels. On pocket beaches where several profiles were established there were no measurable exchanges of sediment along the beach.

By contrast pocket beaches (Figure 8C) with a wide wave approach window and bidirectional drift have the widest sweep zones, much wider than produced by shore normal changes alone. On pocket beaches persistent waves from one direction erode the updrift end of the beach, this sediment is deposited

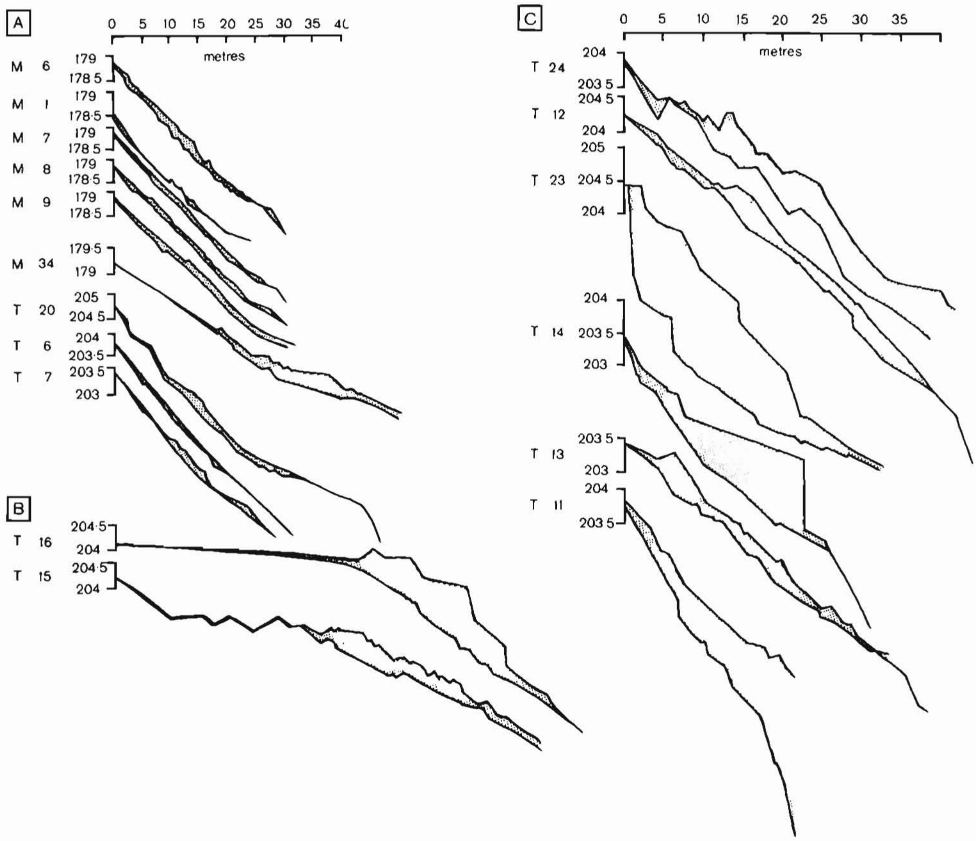

Figure 8. Representative sweep zone envelope curves from Lales Manpouri and Te Anau. (A) High and low energy beaches with a narrow wave approach window. (B) Cuspate foreland beaches, and (C) Pocket beaches with a wide wave approach window.

at the downdrift end while the center of the beach undergoes little change. Updrift erosion takes the form of cliffing, degrading the entire beach profile, whereas downdrift deposition is in progradational ridges (Figure 9). A shift in wave approach and reversal in transport directions reverses this sequence of changes. The net result is continual adjustment and re-orientation of the plan shape of the beach in response to changing wave conditions. On cuspate forelands (Figure 8C) similar changes in wave approach direction produce pulsational movement of sediment backwards and forwards around the foreland.

Volumetric Changes

Volumetric changes between beach surveys are largest on the sand beaches and decrease to the less mobile gravel and pavement beaches (Table 1). Gains and losses to the beach system are largest (12 m^3 m^{-1}) on beaches with a wide wave approach window, reflecting the alongshore transport of sediment in and out of the beach profile. On beaches with a narrow window and negligible alongshore transport volumetric changes are very small (typically < 0.3 m^3 m^{-1}). No relationships could be established between volumetric changes and either the water level range during the intersurvey period and/or rising or falling trends within the record. This, coupled with the lack of correlation between volumetric changes and the exposure to wave activity (effective fetch), suggest that shore normal changes to the profile form are contained within the beach sediment budget requiring no net gains or losses of sediment from the system. However, the volume of mobile sediment within the sweep zone (*i.e.* gross volumetric change) increases as a function of lake level range between surveys (Figure 10). Therefore while there are no net gains or losses to the profiles associated with lake level fluctuations the profiles are reworked more extensively under fluctuating levels

Figure 9A. Beach changes in response to the alongshore transport of sediment, Moonlight Beach, Lake Te Anau (T23, T12, T24), a coarse sand pocket beach exposed to a wide wave approach window. Recession at the eastern end of the beach (T23) and deposition at the western end (T24), nearest the camera, resulting from persistent southeast storm waves.

SIMILARITIES AND DIFFERENCES BETWEEN BEACHES

Beaches around Lakes Manapouri and Te Anau show many similarities to ocean and large lake shores. The morphology of gravel and mixed beaches is similar to that on ocean beaches, while the ridge and runnel morphology of sand beaches differs little from that described on Lake Michigan and the Atlantic coast (DAVIS *et al.*, 1972). Changes in the beach profile in response to fluctuating water levels conform to the Bruun Rule developed for ocean shores and shown to be applicable to large lakes. However, there are some fundamental differences between large lake/ocean beaches and the small lake beaches. Most of these differences can be accounted for by the low levels of wave energy and different water level regimes.

Table 1. Average volumetric changes by beach type.

	Manapouri	Te Anau
Pavement Beaches	0.40 m^3m^{-1}	0.37
Gravel, mixed sand gravel	0.41	0.44
Sand	0.48	1.43

On small lake beaches the size of sediment in transport is limited by the wave energy capable of being generated within the restricted fetch. As a result pavement beaches form, protected and stabilized by an immobile lag veneer. The size of the lag and winnowed sediments increases with the fetch and potential wave energy. On low energy limnic shores, subjected to oblique wave approach and a high potential for littoral drift, pavement beaches can be the dominant beach type and play an important role in both limiting littoral drift and stabilizing the beach profile. By comparison pavements are rare on large lake/ocean beaches where the size of sediment in transport is seldom limited by wave energy.

On small enclosed bodies of water the generation and decay of fully arisen seas takes only minutes or hours. Direct dependence of sea state on weather conditions can produce long periods during which the lake is flat calm. Calm conditions, in conjunction with rising lake levels, can drown beach forms, particularly if composed of coarse sediments. In low energy environments changes in still water level produce relatively large shore normal movements in the zone affected by wave activity (PICKRILL, 1983), consequently beach forms can be submerged and remain unaltered for long periods. Prolonged flat calms are uncommon on large lakes and oceans and submergence of beach forms is rare. Wave energy is large relative to water level movements and submerged features are soon reshaped.

The narrow range of wave conditions generated over short fetch lengths limits the range of morphologies produced on the beach. Unlike large lake/ocean beaches, variations in energy levels and seasonal variations in wave climate have little effect on the profile. Consequently shore-normal beach changes are largely controlled by the elevation at which wave energy strikes the beach rather than by energy variations within the wave climate. Within the Bruun Rule onshore-offshore exchanges produce sweep zone envelopes that contain a range of morphological forms that can be produced at any elevation on the foreshore without altering the fundamental geometry of the profile. The beaches are in equilibrium with the range of wave energies and

Figure 9B Progradation of the eastern end of the beach 4 days later after strong westerly winds

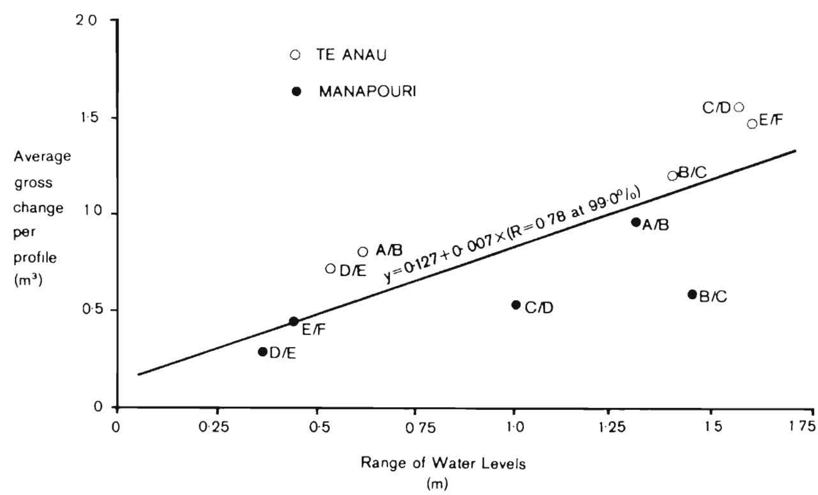

Figure 10. Gross volumetric changes per intersurvey period plotted as a function of the range of water levels between surveys.

the regime of lake levels such that shore/normal exchanges of sediment are minimized and contained within the sediment budget of the beach face.

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