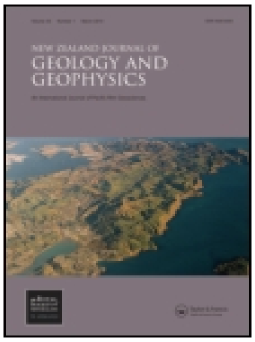

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A sediment budget for the east coast between Oamaru and Banks Peninsula, South Island, New Zealand

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Abstract Two beach systems, the Waitaki (84 km) and Canterbury (136 km), separated by Timaru Harbour breakwater, are considered. Established input (all units in Mt/year; 1 Mt = 10^6 t) to the Waitaki is 0.82 bedload and 2.0 suspended load; to the Canterbury, 1.9 and 15.0. Additional unmeasured abnormal load from intense storms and earthquakes may double the suspended load estimates. Inputs from rivers and eroding seacliffs account almost equally for bedload, but most suspended load is from the rivers. Sediment supplied to both beach systems is moved predominantly northeastward in the Nearshore Transport Zone (NTZ). The inner part includes the steep, coarse-grained, reflective beach and surf zone, the latter being generally narrow or nonexistent. Here, almost all the coarse beach sediment is transported in the swash-backwash zone where about 95% is abraded to mud, the remainder accumulating along Kaitorete Barrier. The outer part of the NTZ extends seaward from the surf zone, for 3–15 km across the inner continental shelf, to depths of 30–60 m. Here, the very fine sand is moved as bedload, and mud as suspended load, in a net northeasterly direction, by waves and currents. Banks Peninsula traps 0.26 Mt/year of the suspended load and bedload in the inlets and 5.5 Mt/year on the shelf around the peninsula. The remaining 11.0 Mt/year is lost to the middle and outer Canterbury Shelf or carried northward into both the Conway and Hikurangi Troughs.

Keywords sediment budget; coast; rivers; rates; erosion; transport; abrasion; deposition; Canterbury; Waitaki; South Island

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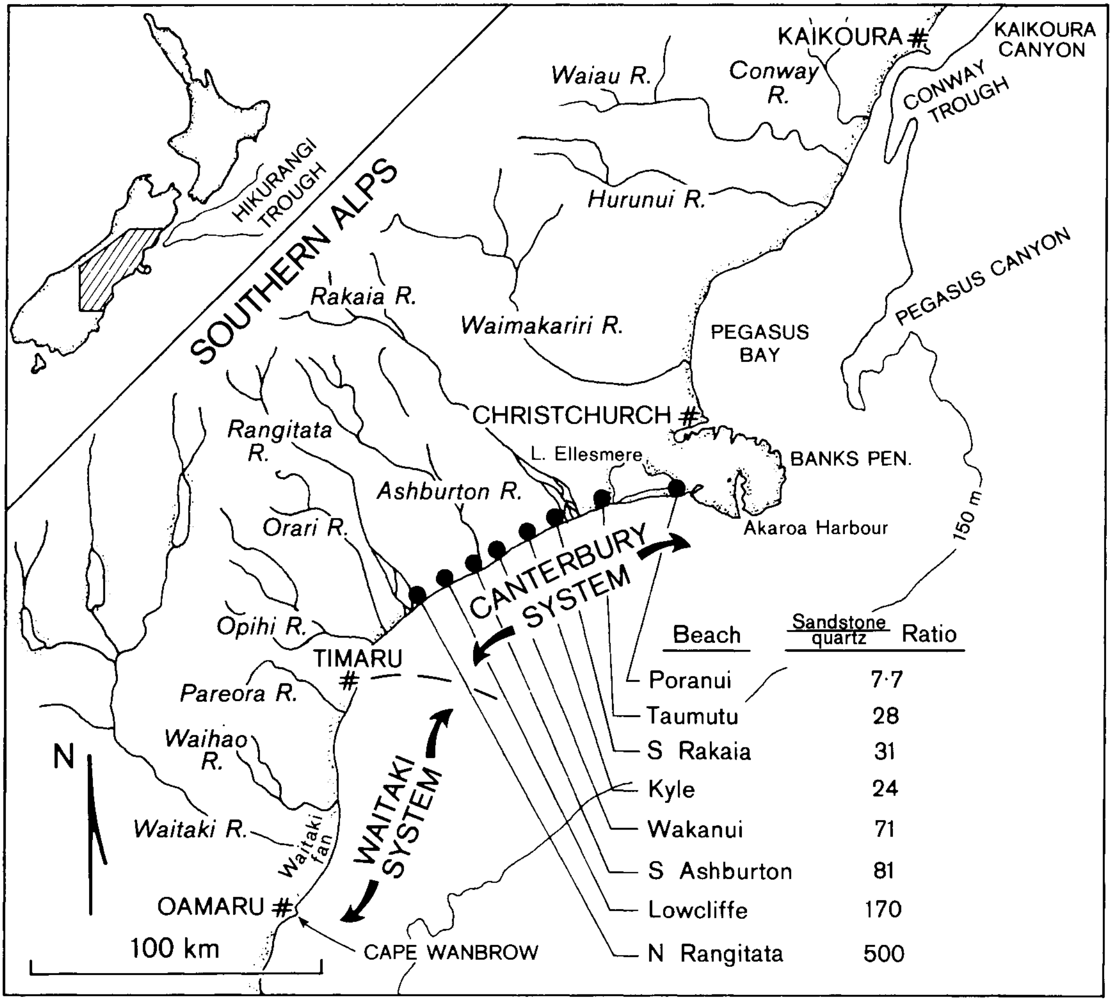
INTRODUCTION

Prior to 1879, the 220 km length of smoothly curved coastline between Oamaru and Banks Peninsula consisted of a single beach system along which sediment was transported by a strong net northeasterly longshore drift. Between 1878 and 1906, shore-connected breakwaters were constructed at Timaru (Tierney 1977) dividing the coastline into 2 beach systems—the Waitaki (84 km long) to the south and the Canterbury (136 km long) to the north (Fig. 1). The division does not extend seaward past the influence of the breakwaters, thus there is continuity offshore between the 2 beach systems.

The beaches within both systems are a mixture of greywacke gravel and sand (McLean & Kirk 1969) supplied from eroding seacliffs and from rivers. The Waitaki beach system is fed by 1 large river, the Waitaki, and 2 smaller rivers, the Waihao and Pareora. The Canterbury beach system is fed by 2 large rivers, the Rangitata and Rakaia, and 3 smaller rivers, the Opihi, Orari, and Ashburton. All drain the rapidly eroding Southern Alps (Fig. 1) and carry large quantities of sediment during peak flows. Deltas have not formed on the coastline because of the smoothing effect of the strong net northeasterly longshore drift.

Within the Waitaki system, all but 4 km is actively retreating because of coastal erosion. Of the eroding part, about 50 km are seacliffs of late Pleistocene outwash gravels, retreating at an average rate of 1.1 m/year, with a maximum of 2.0 m/year along the South Waitaki fan. The remainder is a barrier beach that is eroding at up to 0.9 m/year (Gibb 1978). A small amount of accretion is taking place at Timaru and Oamaru (Fig. 2) at the distal ends of the system, with maximum accretion of up to 5.7 m/year occurring at South Beach, Timaru (Tierney 1977).

Within the Canterbury system, all but 16 km is actively retreating because of erosion. Late Pleistocene gravels of the Canterbury Plains form 66 km of seacliffs within the middle part and are eroding at an average rate of 0.6 m/year (Speight 1950; Gibb 1978), with a maximum of 1.4 m/year (Gibb 1978) about 16 km north of the Ashburton River mouth. In the southern part, a barrier beach across the Washdyke Lagoon (Fig. 2) is being rolled back up to 4.3 m/year, the rate decreasing progressively northwards to 1.0 m/year near the Opihi River mouth (Gibb 1978). In the northern part, between the Rakaia River mouth and the



Beach	Sandstone/quartz Ratio
Poranui	7·7
Taumutu	28
S Rakaia	31
Kyle	24
Wakanui	71
S Ashburton	81
Lowcliffe	170
N Rangitata	500

Fig. 1 The eastern South Island region covered by the present study, and beach sediment sampling sites mentioned in the text. The edge of the continental shelf is shown by the 150 m isobath.

outlet to Lake Ellesmere, the barrier beach is rolling back up to 3.1 m/year (Gibb 1978). From the outlet to Banks Peninsula lies Kaitorete Barrier along which the southern third of coast is actively eroding, the middle third is static, and the northern third is advancing from accretion up to 0.5 m/year near Poranui (Armon 1970). The barrier encloses Lake Ellesmere and Lake Forsyth, once shallow coastal embayments, and is the final destination for the net northeasterly drift of all the gravel and a portion of the sand, the rest either bypassing, or being trapped in, the bayheads and inlets of Banks Peninsula. In contrast to the dominantly eroding coasts, sediment is accumulating at rates of 1–3 m/1000 years on the inner continental shelf around Banks Peninsula in water depths up to 60 m (Herzer & Lewis 1979).

No sediment budget has previously been established for the Canterbury system, but Kirk & Hewson (1978) have attempted to establish one for the Waitaki. They estimate a total sediment input of 360 686 m^3/year (0.65 Mt/year), of which the seacliffs contribute 54.4% and the Waitaki River 45.6%. Some 84% of Waitaki-derived sediment is thought to move north and the remainder south. Of the total input, 72.4% is stored at South Beach, 17.2% is commercially extracted from the beach, and the remainder (10.4%) is transported northward into the Canterbury system. Kirk & Hewson make no reference to the considerable losses caused by abrasion during longshore transport, nor to the post-breakwater-construction accumulations of sediment at Oamaru.

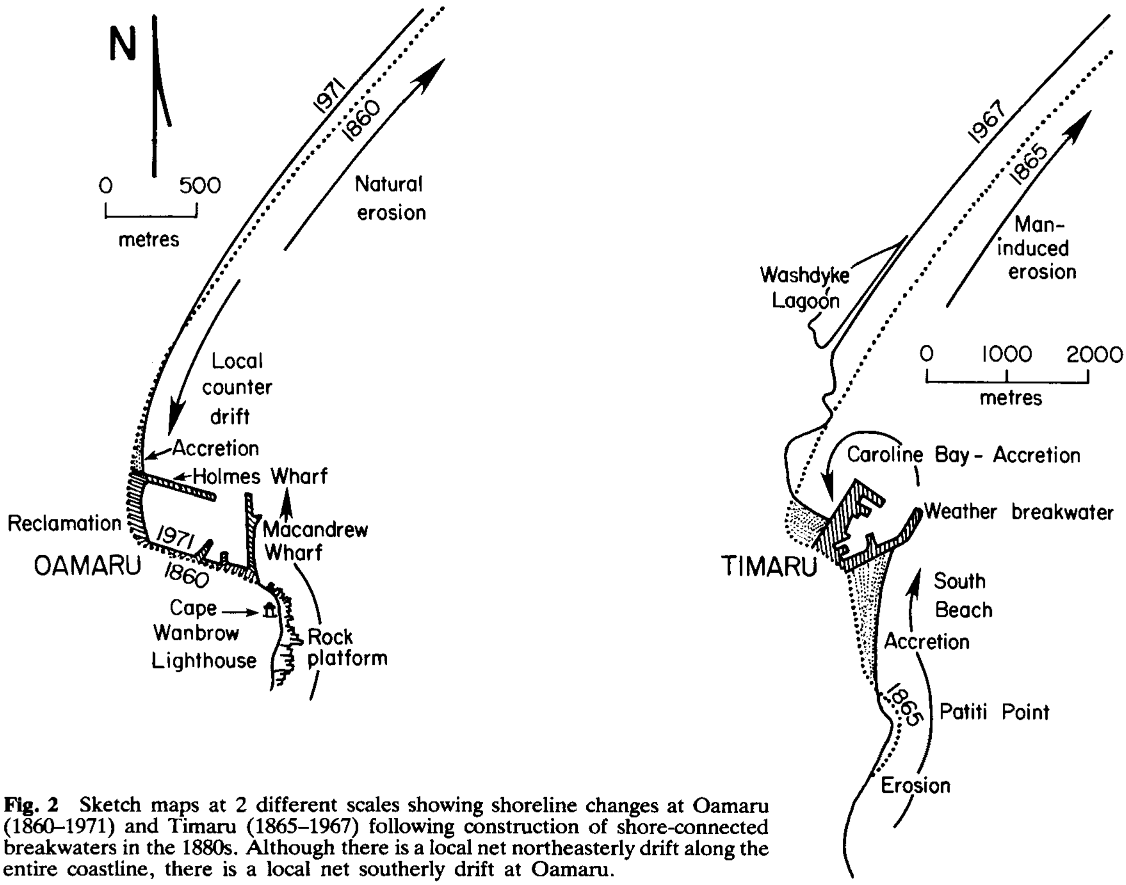


Fig. 2 Sketch maps at 2 different scales showing shoreline changes at Oamaru (1860–1971) and Timaru (1865–1967) following construction of shore-connected breakwaters in the 1880s. Although there is a local net northeasterly drift along the entire coastline, there is a local net southerly drift at Oamaru.

In this paper, we discuss rates of sediment input and output for both beach systems and attempt to quantify a sediment budget (see Table 7). All units are given in megatonnes per year (Mt/year; 1 Mt = 10^6 t) by assuming densities of 1.8 t/m^3 for gravel and 1.25 t/m^3 for very fine sand and mud (size classes from Wentworth 1922). The present study brings together aspects of doctoral research carried out by Adams (1978a) into river transport and catchment erosion rates in the South Island and by Gibb (1979) into longshore transport and rates of coastal erosion and accretion around New Zealand. Further, Adams is responsible for pebble abrasion work and Gibb for shelf sedimentation rates.

NEARSHORE TRANSPORT ZONE

Sediment supplied to both the Canterbury and Waitaki beach systems is moved in the **Nearshore Transport Zone** (NTZ) which consists of an inner and an outer part. Beyond the outer part is the middle and outer continental shelf, the study of which is beyond the scope of this paper. Note that the term "bedload" used here for transport in the NTZ refers to very fine sand, and "suspended load" refers to mud, whereas for the rivers mentioned later that supply sediment to the NTZ, suspended load includes both mud and very fine sand.

Outer NTZ

The outer NTZ extends seaward from the surf zone for 3–15 km, depending on the locality, to depths of 30–60 m. Here, wave orbital motion stirs up very fine sand (bedload) and mud (suspended load) and places the particles into oscillatory motion. Once stirred into suspension by the waves, the bottom sediment can be moved in the direction of any superimposed current regardless of velocity (Bagnold 1963). On the inner Canterbury continental shelf, the bedload is transported northeastward by the combination of the northerly flowing Southland Current, tidal currents, prevailing southerly swell, and wind-driven currents (Carter & Herzer 1979).

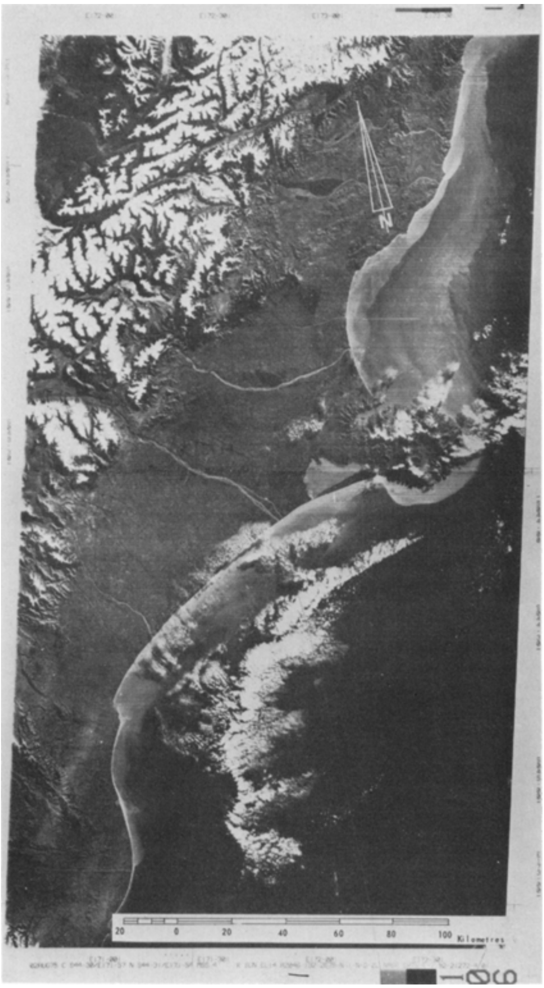


Fig. 3 Nearshore sediment plumes revealed on LANDSAT II images of the study area taken on 2 August 1975, Band 4; scene identification numbers E-2192-21265; E-2192-21272. Photographs by courtesy of NASA.

Sediment plumes revealed by LANDSAT II imagery (Fig. 3) indicate that suspended load is tranported in the same general direction.

Once out of the influence of wave orbital motion, the very fine sand rapidly settles out, as evidenced by the very low terrigenous sand concentrations (<10%) in sediment traps such as the Conway and Hikurangi Troughs (Dr L. Carter, N.Z. Oceanographic Institute, DSIR, pers. comm. 1982). By contrast, the mud remains suspended much longer and is therefore moved greater distances. According to Herzer (1979), the transport of very fine sand in the Canterbury Bight is mainly confined to within 15 km of the beach, out to a depth of about 30 m. Southerly gales and storms confine the sand transport within the outer NTZ by generating a shoreward component of flow on the seabed. For mud, the situation is slightly different. Although transported northeastwards by the same processes, much of the mud has accumulated over the continental shelf beyond the outer NTZ (Herzer 1981)

Between the Rangitata and Rakaia Rivers, and off the Waitaki River, the sediments are pebble dominant (Herzer 1981, fig. 10), but, because the pebbles extend 30 km offshore, they are most likely relict deposits, drowned during the Postglacial transgression. That they are not buried by sand or mud, although close to modern sediment sources, suggests that this part of the outer NTZ is acting as an efficient **conveyance zone**. Evidence presented by Tierney (1977) and Kirk (1978) off Timaru further substantiates this contention. At Timaru, fine sand that accumulates within the harbour is removed by dredging and dumped 3 km northeast of the port in 11 m water depth. A comparison by Tierney (1977) of early surveys with recent hydrographic surveys revealed that the depths at the dumping grounds showed no change, which suggests the dredgings are transported away very quickly by offshore currents. From a fluorescent sand tracer experiment, about 2.5 km northeast of the port in 8 m water depth, Kirk found after 92.5 h of moderate southeasterly sea conditions that sand was carried up to 40 m in a net northwesterly direction towards the shore, from the injection point.

Further north, Banks Peninsula causes a constriction and an acceleration of the transporting currents. Surveys by Herzer (1977) indicate a narrowing of the outer NTZ from 15 to 3–4 km from the shore. The belt of very fine sand transported along the inner shelf as bedload extends offshore to a depth of 60 m and mud is virtually absent (Herzer 1977, 1979). Some of the sand moving around the peninsula is trapped by the bayhead beaches on the eastern extremity (Dingwall 1974), but the greater volume continues northwards to form a 40 km long submarine spit across the entrance of Pegasus Bay. Very fine sand bypassing Banks Peninsula does not appear to reach the northern shoreline as it does further south at Otago Peninsula (Andrews 1973) because a band of mud separates the outer sandy bank from the sandy nearshore seabed in Pegasus Bay (Cullen & Gibb 1966; Herzer 1981). Inferred transport directions around the peninsula are shown in Fig. 4.

In Pegasus Bay, sedimentary and geomorphic evidence suggests there is a local net southerly drift of the locally river-derived beach sediments (Fig. 4). Grainsize decreases, and sorting of beach sediments

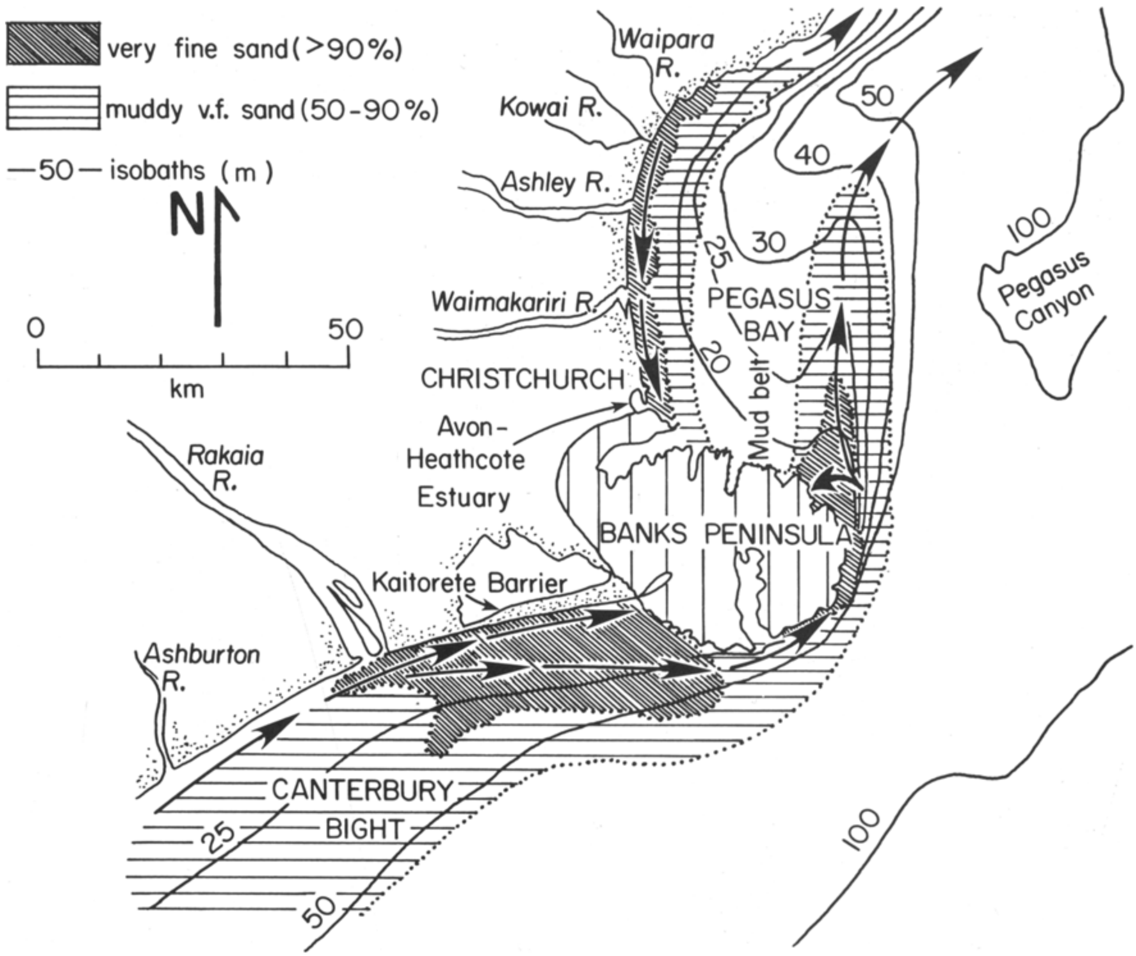


Fig. 4 Sketch map showing inferred directions of net drift (arrows) around Banks Peninsula based on sedimentologic (textural, petrographic) and geomorphic evidence. Bathymetry in metres is from Herzer (1977) and sediments from Cullen & Gibb (1966) and Herzer (1981).

improves, southwards, and the relative abundance of biotite and chlorite increases in the same direction (Blake 1968). Heavy minerals from Waimakariri River were identified by Reed (1951) at the entrance to the Avon–Heathcote Estuary. The Waimakariri River mouth migrates south and the South Brighton Spit has grown southwards across the estuary. The southerly counterdrift is attributed here to Banks Peninsula sheltering Pegasus Bay from the prevailing southerly swells. In northern Pegasus Bay the Ashley, Kowai, and Waipara River mouths oscillate in position, probably reflecting an oscillatory longshore drift pattern. The net northeasterly pattern of transport starts to predominate again north of Pegasus Bay, as shown by the sediment plumes in Fig. 3.

Inner NTZ

The inner NTZ includes the beach and the surf zone, the latter being generally narrow or nonexistent throughout the study area. The foreshore slopes of the steep, coarse-grained beaches average 6° (McLean & Kirk 1969) and beach widths seldom exceed 40 m between the eroding seacliffs and the sea. Longshore bar/channel topography is rarely, if ever, generated (Kirk 1975) and relatively deep water reaches the base of the intertidal beach. Hence, breaking waves dispel most of their energy directly on the beach, plunging upon or surging up the beach face with maximum runup. Most, if not all, sediment transport is therefore in the swash-backwash zone where the sediment particles ε e pushed and rolled across the beach face, tracing a sawtooth path in the direction of wave travel.

For the study area, the prevailing swell comes from the southerly quadrant (Hodgson 1966; Tierney 1977; Pickrill & Mitchell 1979), generating a strong regional net northeasterly longshore drift between Oamaru and Banks Peninsula. According to Herzer (1979), gravel and sand are transported northeastwards along the beach by the prevailing southerly swell, but are stopped by Banks Peninsula. They are not carried offshore. For steep, coarse-grained beaches in Australia, Wright (1980) also found that storage of active sediment was primarily in the "inter-tidal and subaerial beach" rather than in the surf zone or outer NTZ.

As a consequence of the net northeasterly drift, the mouths of the Waitaki, Ashburton, and Rakaia Rivers migrate northeastwards during low flows (Kirk et al. 1977), and at Timaru the shore-connected breakwaters block most, if not all, of the net drift of gravels, causing accretion to the south and serious erosion of the coast to the north (Fig. 2). A portion of the net northeasterly drift of fine sand is trapped inside the harbour and in Caroline Bay. Although the northeasterly drift predominates within the study area, locally generated waves from the northeast quadrant set up a subordinate longshore drift which distributes a portion of the river-derived bedload a short distance southwest of the river mouths. Carter & Herzer (1979) noted a similar southerly counterdrift in this area.

Comparisons of vertical aerial photographs taken between 1936 and 1976 show that the beach has remained about 40 m wide along the entire coast during this period. This indicates that the sediment supplied episodically from the large rivers during floods, and from eroding seacliffs, is rapidly dispersed alongshore by wave action. An important function of the beach, therefore, is that it, like areas of the inner continental shelf, acts as a **conveyor** of the net northerly drift. As discussed later, the gravel is subjected to considerable abrasion by wave action during longshore transport.

SEDIMENT INPUT

Seacliff erosion

Gravel, sand, and some mud are supplied to the 2 beach systems from eroding seacliffs cut in late Pleistocene outwash gravels capped by varying thicknesses of loess. In the Waitaki cliffs, the loess is 10 m thick at Oamaru, but tapers progressively to about 0.5 m, 8 km north of Oamaru. In the Canterbury cliffs, the loess is seldom more than 1 m thick.

The amounts of sediment supplied were calculated by the End Area method and Trapezoidal rule (Bannister & Raymond 1972) and are given in Table 1 (Waitaki) and Table 2 (Canterbury). The results show that 0.60 Mt/year of gravel and sand, and 0.1

Table 1 Volume of sediment supplied to the Waitaki beach system from eroding seacliffs cut in late Pleistocene gravels and loess. Volumes (*V*) are calculated from equal spaced (*D*) cross sections (*A*) by the following formula (Bannister & Raymond 1972): $V = D.[(A_1 + A_n)/2 + A_2 + ... + A_{n-1}]$. Cliff heights and lengths of coastal sections were determined from NZMS 1, 1: 63 360 topographic maps. Cliff recession rates are averaged from net rates given by Gibb (1978, appendix 1). Cliffs are assumed to have remained parallel during retreat. Hence, cross-sectional areas are calculated by height times recession rate.

Cliff section	Recession rate (m/year)	Cliff height (m)	Cross-sectional areas (m^2) A_1	A_2	A_3	A_4	A_5	A_6	D (km)	Volume (m^3/year)	Percent gravel
South	1.0	10	10						3.48		75
Waitaki		12		12							
Fan		15			15						
		15				15					
		16					16				
		17						17		249 000	
North	1.21	12	14.52						6.85		95
Waitaki		9		10.89							
Fan		6			7.26					149 000	
St	0.28	6.1	1.71						2.00		40
Andrews		7.0		1.96							
		10.5			2.94						
		11.7				3.28				14 000	
TOTAL	From 37 km of eroding seacliffs										
INPUT	gravel = 334 000 m^3/year = 0.6 Mt/year mud = 78 000 m^3/year = 0.1 Mt/year									412 000	81

Mt/year of mud are supplied to the Waitaki system, and 0.89 Mt/year of gravel and sand, and 0.03 Mt/year of mud to the Canterbury system. The greater thickness of loess in the Waitaki cliffs accounts for the greater proportion of mud supplied to the Waitaki system (c. 20%) compared with that to the Canterbury system (c. 5%).

River input

The rivers flowing into the Waitaki and Canterbury systems are wide and braided. They carry coarser sand and gravel as bedload and finer sand and mud as suspended load compared with transport processes in the outer NTZ.

Table 3 gives input rates for bedload and suspended load to both beach systems. Bedload rates were calculated by Adams (1980) from the following formula derived by him from the Einstein-Brown formula:

$$Y = 174 \times 10^6 \, nSQ/a \exp(b)$$

where Y = mean annual bedload in tonnes per year; n = Manning's "n", taken to be 0.03; S = channel slope in radians; Q = mean annual river discharge in m^3/s.

Table 2 Volume of sediment supplied to the Canterbury beach system from eroding seacliffs cut in late Pleistocene gravels. See caption to Table 1 for details.

Cliff section	Recession rate (m/year)	Cliff height (m)	Cross-sectional areas (m^2) A_1	A_2	A_3	D (km)	Volume (m^3/year)	Percent gravel
Raikaia River to	0.71	7.62	5.41			17.25		95
Ashburton River		16.76		11.9				
		20.12			14.3		375 000	
Ashburton River	0.39	18.29	7.13			6.25		95
to Hinds River		16.76		6.54				
		9.75			3.80		75 000	
Hinds River to	0.44	5.76	2.53			6.45		95
Rangitata River		12.19		5.36				
		11.58			5.10		59 000	
Rangitata River	0.33	9.14	3.02			3.10		95
to Orari River		7.32		2.42				
		3.66			1.21		14 000	
TOTAL	From 66 km of eroding seacliffs							
INPUT	gravel = 497 000 m^3/year = 0.89 Mt/year						523 000	95
	mud = 26 000 m^3/year = 0.03 Mt/year							

Table 3 Load carried by rivers draining into the Waitaki and Canterbury beach systems. Bedload from Adams (1980); suspended load from (a) Adams unpublished, (b) estimated from Orari rate, (c) Adams (1980), (d) Thompson & Adams (1979), (e) estimated from South Ashburton River at Mount Somers (Thompson & Adams 1979).

River	Mean flow (m^3/s)	Sediment load (Mt/year) Bedload		Suspended	
WAITAKI SYSTEM					
Waitaki	326	0.178		1.6a	
Waihao	~6	0.015		0.14b	
Pareora	~8	0.031		0.17b	
Sub-total:			0.22		1.9
CANTERBURY SYSTEM					
Opihi	~30	0.067		0.7b	
Orari	9.3	0.027		0.26c	
Rangitata	90	0.281		2.61d	
Ashburton	~20	0.073		0.14e	
Rakaia	190	0.466		8.56d	
Sub-total:			0.91		12.3
TOTAL:			1.13		14.2

a and b are parameters of the equation $f = \exp(-aq-b)$ used to represent the flow distribution curve. f = the fraction of time that a given value of q is exceeded; q = ratio of instantaneous discharge Q_i to mean flow Q.

As shown by Adams (1980, p. 42) there is good agreement between the bedload transport rate calculated by the above formula and empirically determined gravel extraction rates that approximate the natural replacement rate in rivers where the extraction rates have been determined. The long-term erosional retreat of the seacliffs is shortening and steepening the channels of the rivers considered here. The shortening ensures that there can be no substantial storage of sediment in the lower channels, as argued by Kirk et al. (1977, p. 243). The calculated bedloads are, therefore, considered realistic estimates of the amount delivered to the beaches.

The suspended loads were taken from a variety of sources including Thompson & Adams (1979, table 4) where the following formula was derived:

$$Y = 31.56\ hC_5Q$$

where Y = mean annual suspended load in tonnes per year; h = an integral variable of parameters a and b of the flow distribution curve and the slope of the sediment rating curve (see Thompson & Adams 1979 for details); C_5 = sediment concentration at 5 times mean flow in g/m^3; Q = mean annual discharge in m^3/s.

Table 3 indicates that 0.2 Mt/year of bedload and 1.9 Mt/year of suspended sediment are supplied to the Waitaki system, and that 0.9 Mt/year of bedload and 12.3 Mt/year of suspended load are supplied to the Canterbury system.

Adams (1980) discussed the importance of abnormal sediment supply events resulting from high-intensity rainfalls and from earthquakes. The abnormal events are not measured by the suspended sediment samples used to calculate the suspended loads in Table 3. From other evidence, Adams concluded that the total long-term suspended sediment yield, including abnormal loads, may well be twice the normal loads shown in Table 3. By contrast, in braided rivers, the channel slope is probably adjusted to the long-term bedload yield, so bedload rates calculated from the channel slope include both normal and abnormal loads.

Longshore drift

Prior to the construction of the shore-connected breakwaters at Oamaru and Timaru in the 1880s, the regional net northeasterly drift was uninterrupted along the entire length of coastline between Oamaru and Banks Peninsula. The post-construction accumulations of coarser sand and gravel which is trapped updrift of the breakwaters, and of finer sand trapped within the harbours, provide an estimate of the former longshore transport rates.

At Timaru, Tierney (1977) compared survey and dredging records from 1879 to 1967. He calculated an average minimum net northeasterly transport rate of 206 × 10^3 m^3/year, of which 60 × 10^3 m^3/year (0.11 Mt/year) was gravel and coarser sand that had accumulated against the weather breakwater, and the remainder was finer grained sand that had accumulated within the harbour (115 × 10^3 m^3/year) and in Caroline Bay (31 × 10^3 m^3/year) (Fig. 2). According to Tierney, little, if any, gravel bypasses the weather breakwater, so the rate represents the total gravel and coarser sand in transport. The rate for finer grained sand is a minimum estimate, however, as a significant unknown portion continues downcoast in the outer NTZ. As mentioned previously, the 115 × 10^3 m^3/year (0.14 Mt/year) of finer grained sand that accumulates within the harbour is removed by dredging and put back into the outer NTZ in 11 m water depth, where it is transported away in a net northeasterly direction by the combination of wave action and offshore currents. Based on his tracer experiment and dispersion of the dumped dredgings, Kirk (1978) estimated gross transport rates across the nearshore shelf by Timaru, out to a depth of 11 m, of 650–1500 × 10^3 m^3/year (0.81–1.90 Mt/year). As will be shown later (see Table 7), these estimates are of the right order of magnitude, but are probably conservative.

At Oamaru, there is a local net southerly counterdrift of gravel and sand. Surveys made of the coast in 1860 and 1971 show that in the period following the construction, in about 1880, of the lee breakwater (Holmes Wharf) the shoreline north of the breakwater advanced 63 m to a depth of about 5 m (Fig. 2). As the height of the present berm crest is about 4 m above mean sealevel, an accretion thickness of 10 m is estimated. If the accreting section is 360 m long and 10 m thick, with accretion decreasing from 0.7 m/year in the south to zero in the north, then a local net southerly transport of gravel and sand of 1.3 × 10^3 m^3/year can be estimated.

Between 1880 and 1977, a small amount of gravel derived from very slow erosion of the volcanic rock seacliffs at Cape Wanbrow has accumulated against the weather breakwater (Macandrew Wharf) from the undernourished regional net northeasterly drift. In January 1977, Gibb made a field estimate of 250 m^2 for the area of accretion. By assuming a thickness of 10 m for the accretion, he estimated a northerly transport of gravel around Cape Wanbrow of 25 m^3/year. The amount is trivial and is thus neglected in assessing the sediment budget. No data are available for the silting up of Oamaru Harbour, although it is known locally that appreciable shallowing has occurred since dredging was discontinued.

SWASH-BACKWASH ABRASION

Abrasion of beach gravel in the swash-backwash part of the inner NTZ was quantified in 2 ways: (1) by comparing the volume of gravel input into the Canterbury beach system with the volume of gravel output at Kaitorete Barrier, the final sink for the regional net northeasterly drift; and (2) by examining the changing proportion of the various gravel lithologies along the Canterbury beach. The first is described later under "Sediment output" and the second is described now.

Only visual estimates were made of the changing proportion of the various lithologies on beaches south of Rangitata River, but they confirm that abrasion on these beaches is similar to that quantified below for beaches north of the river. Gravel supplied to the Canterbury beach is composed of lithologies in the following order of dominance: sandstone ("greywacke"), argillite, rhyolite, and quartz. The rhyolite,.containing minor chalcedony and agate, comes from the Mount Somers Volcanics in the foothills of the Southern Alps, and the sandstone, argillite and quartz come from the greywacke-suite rocks of the Southern Alps. The quartz occurs as veins in the greywacke, but the proportion of veins to bedrock at source is not known. Quartz is a small part, perhaps 0.1%, of the river gravels. Although all 4 lithologies are abraded during longshore transport, quartz is the most resistant and it remains when the others have abraded away.

The relative resistance to abrasion of beach gravels of the 4 lithologies was measured in a drum tumbler of the kind used for gemstone polishing (Adams 1978b). Although tumblers do not simulate the swash-backwash beach action very well, they are simple to use and provide a measure of the relative abradability of pebbles tumbled together.

The results (Table 4) are expressed as abrasion coefficients for length (α_D) to fit the Sternberg equation (Blatt & Middleton 1972):

Final weight

$$= \text{initial weight} \times \exp(-3\alpha_D \times \text{distance})$$

where the distance (in kilometres) is 60% of the distance moved by the tumbler drum wall and is reduced because all gravels do not move along the drum wall. Table 4 shows that, on average, the quartz gravels are 4.8 times as resistant as the sandstone, 4.5 times as resistant as the argillite, and 2.8 times as resistant as the rhyolite. Brown gravels of sandstone, from the slightly weathered cliff gravels, abrade 40% faster than fresh sandstone gravels. The abradability of the gravels changes along the beach as the less-resistant gravels are

Table 4 Abrasion coefficients (α per km) for representative pebbles of 5 lithologies taken from 4 of the sampling sites shown on Fig. 1. Values from Adams (1978b).

Lithology	Beach Lowcliffe	Kyle	Taumutu	Poranui	Mean
Sandstone	0.0015	0.00089	0.00060	0.00063	0.00091
Argillite	0.00096	0.00086	0.0011	0.00048	0.00085
Rhyolite	0.0010	0.00030	0.00058	0.00021	0.00052
Quartz	0.000078	0.00021	0.00022	0.00024	0.00019
Brown sandstone	0.0020	0.0011	0.00065	–	0.0013

Table 5 Lithologic composition of cobbles (80–120 mm) and pebbles (30–60 mm) from the 8 sample sites shown on Fig. 1. Values from Adams (1978b).

	Cobbles			Pebbles		
Beach	Greywacke	Argillite	Rhyolite	Greywacke	Argillite	Rhyolite
North Rangitata	500	13	3.5	20	0.69	0.16
Lowcliffe	170	5.0	0.33	32	1.4	0.29
South Ashburton	81	2.1	0.30	44	1.9	0.08
Wakanui	71	1.4	0.14	27	1.2	0.04
Kyle	24	0.90	0.09	25	0.91	0.04
South Rakaia	31	1.2	0.01	10	0.72	0.01
Taumutu	28	0.88	0.01	15	1.3	0.01
Poranui	7.7	0.26	<0.01	2.5	0.26	0.01

abraded away. The abrasion coefficient roughly halves for sandstone, argillite and rhyolite, but remains about the same for the quartz.

Tumbler abrasion coefficients cannot be applied directly to beach gravels because for each metre the gravels move along the beach by longshore drift, they move many metres up and down the beach, and they are also worn by other gravels moving over them. The coefficients can, however, be related to the change in proportion of each lithology.

Gravel lithology was measured at 8 sites along the coast (Fig. 1). At each site a sample of cobbles (80–160 mm) amounting to about 120 kg was sorted and the lithologic fractions weighed. A further sample of about 700 pebbles (30–60 mm) was sorted and the fractions counted. Heavy rain during the sampling period ensured that all gravels were sorted when wet. The lithologic composition of the gravel at the 8 sites is given in Table 5, expressed as ratios of the quartz fraction of each sample.

Figure 5 shows the change in proportion of sandstone to quartz cobbles, on semilogarithmic scales, with sloping lines fitted to the data points that allow for the abrasion of the sandstone, and vertical lines that allow for the diluting effect of the river gravel. The fitted lines assume the rivers to be point sources and ignore the minor southward drift component. The downdrift change is almost entirely the result of abrasion of the sandstone, since the tumbler results show that the quartz abrades at only one-fifth of the sandstone abrasion rate. The slope of the fitted line is equivalent to an abrasion coefficient (α_D) of 0.024/km south of, and 0.017/km north of, the Rakaia River, when the distance is measured as the straightline distance along the beach. The use of the lower value is justified by the tumbler abrasion coefficients which show cobbles to be more resistant north of the river. Comparison with the tumbler average value of 0.00090/km suggests that the cobbles have moved an average of 26 times the straightline distance, tracing a sawtooth path in the swash-backwash zone. Similar results come from analysing the change in argillite (24 times) and rhyolite (50 times) proportions.

Lithologic changes for pebbles parallel the changes in the cobbles, although the quartz content initially declines before increasing. We believe the decline is the result of sandstone pebbles abraded from the coarser sizes being added to the finer.

All gravels supplied to the beach by the rivers have travelled many kilometres from their source in the Southern Alps, hence most are sound and free of defects. Very few clasts on the beach have freshly broken surfaces and the gravels wear by abrasion rather than by fracture. Abrasion of cobbles produces mainly mud, which is washed offshore,

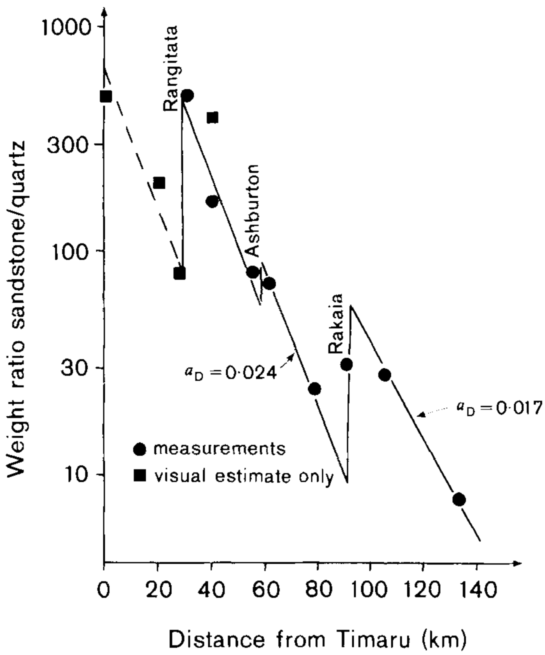
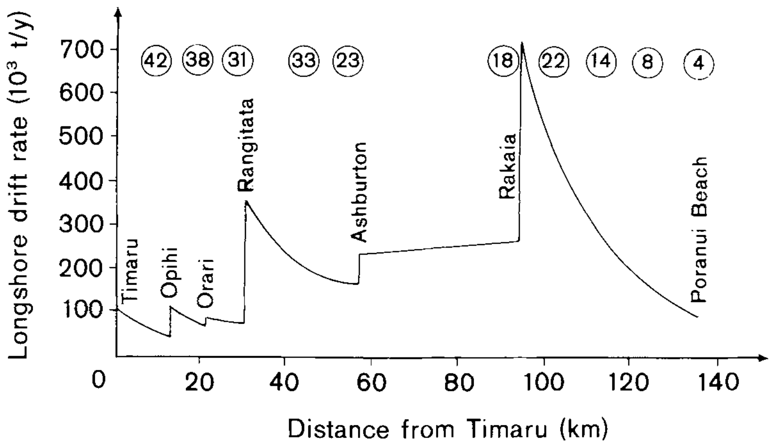


Fig. 5 Semilog diagram graph showing change in the weight ratio of sandstone to quartz cobbles at sites along the Canterbury beach (see Fig. 1). Lines are drawn to show the progressive northward change of the ratio and the effect of inputs of river bedload. Positions of important river mouths are also indicated.

and pebbles that remain on the beach and undergo further abrasion. Only small amounts of sand are produced by abrasion of greywacke gravels (Adams 1980), and the sand produced, if not swept off the beach, is further abraded by the "ball mill" effect of the mobile gravel. The amount of gravel on the beach is thus reduced, and the amount of reduction can be estimated from the change in gravel composition.

One kilometre northeast of the Rangitata River mouth, the ratio of sandstone to quartz is 500:1. At Poranui Beach the ratio is 7.7:1, and if abrasion of the quartz is neglected, only 1.7% of the gravel input remains. Abrasion of the quartz can be estimated from the tumbler abrasion coefficients. A quartz cobble moving half the distance along the Canterbury beach (68 km) and travelling, in total, 25 times this distance, would lose 60% of its weight, so that, in fact, abrasion may account for 99.3% of the input of cobbles. For the same distance, the sandstone:quartz ratio for pebbles changes from 20:1 to 2.5:1. If we assume the abrasion of the quartz as above, then 93% of the pebble size is lost by abrasion.

Fig. 6 Diagram showing net northeasterly longshore transport rates between Timaru and Poranui Beach calculated from longshore transport rates plus gravel input (cliffs are treated as line sources, rivers as point sources) less gravel lost by abrasion. Actual rates are likely to be a smoothed version of the graph. Numbers above the graph give the percentage of gravel input from the south that remains on the beach.



For a single size grade, abrasion is less rapid for smaller than for larger clasts. However, in mixtures of cobbles and pebbles, or of gravel and sand like that on the beach of the Canterbury Bight, the finer sizes are rapidly ground up between the larger sizes (Marshall 1927, p. 511). Thus, although longshore drift is more efficient for moving smaller rather than larger sizes, it is likely that at least 95% of the total gravel and sand input to the Canterbury Bight beach is ground up by abrasion to form mostly mud which is washed offshore, and that less than 5% remains to be deposited on Kaitorete Barrier. In all probability, little, if any, of the Waitaki gravel survives the transport, and most of the gravel forming the barrier is from Rakaia River.

Figure 6 summarises gravel input, transport, and abrasion rates and shows the annual net longshore transport rate calculated from the difference between the net northeasterly longshore drift, plus gravel input, minus gravel lost by abrasion. Between the Rangitata and Rakaia Rivers, the transport rate changes little, as the gravel supplied from the eroding cliffs roughly equals that lost by abrasion. Above the graph in Fig. 6 is the percentage of the gravel input that remains on the beach. These values are in accord with the observed sandstone:quartz ratios given in Table 5.

Of the total gravel input of 1.9 Mt/year into the Canterbury system, about 95%, or 1.8 Mt/year, is lost by abrasion along the 136 km long beach. Thus, the average abrasion rate is 13 400 t/km/year, or a loss of about 7500 m^3 of gravel annually per kilometre length of beach. The rate is a factor of 5, faster than the rates of 900–1600 m^3/km/year found by Zhdanov (quoted in Zenkovich 1967, p. 90) for a more sheltered beach near Sochi.

DYNAMIC BALANCE OF THE BEACH

At the base of the near-vertical seacliffs in the Canterbury and Waitaki systems, the beach mantles a seaward-sloping shore platform cut by the waves in the late Pleistocene outwash gravels. If we take the Canterbury beach to be 40 m wide, 3 m deep, and 136 km long, the volume of beach gravel is 16 000 × 10^3 m^3 (29 Mt), about 15 times the estimated annual input of gravel. Without constant replenishment from rivers, eroding seacliffs, and the regional net northeasterly longshore drift, the volume of the beach would be drastically reduced by both longshore drift and swash-backwash abrasion.

Sediment input from the rivers is episodic, and large quantities of gravel are supplied to the coast during large floods that occur every 3 years or so. At the river mouths, beaches are temporarily widened as a consequence, protecting the seacliffs from marine erosion, thus reducing the supply of gravel from the cliffs. When river input is small, however, longshore drift and abrasion narrow the beach, exposing the cliffs again to marine erosion so that they become the dominant suppliers of gravel. During the retreat of the coast, therefore, a constant beach volume is maintained by sediment input balancing sediment output. The dynamic balance of the beach is maintained by the long-term inputs from the cliffs compensating for the episodic fluctuations in river supply.

Sand and gravel extraction

Extraction of sand and gravel from the beach is generally unwise as it upsets the dynamic balance of the system. If extraction is to proceed, however, the best sites would be from the riverbed, from the beach immediately downdrift (north) of the river

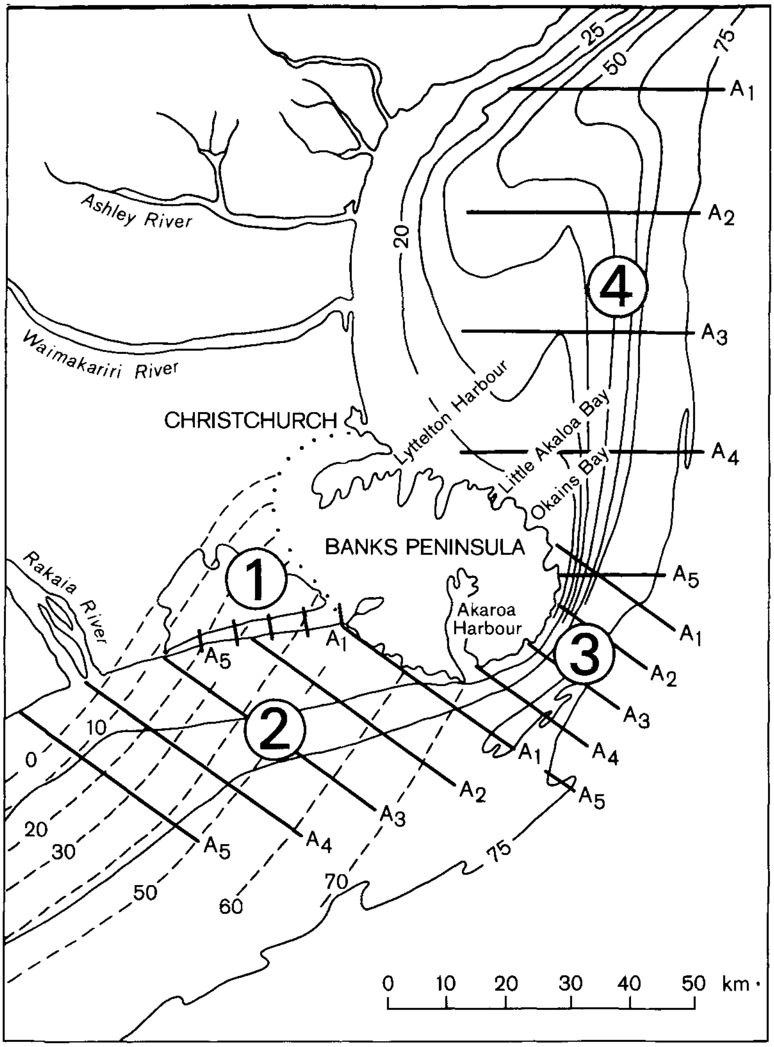


Fig. 7 Location of cross sections (Fig. 8) for each of the 4 areas (①–④), for the calculation of deposition rates (Table 6). Bathymetry (solid lines) and Postglacial Transgression Surface contours (broken lines) are from Herzer (1977) and Gibb (1979).

mouths, and from the northern ends of the Waitaki and Canterbury beach systems.

In terms of increasing the erosion rates, the worst extraction sites on the beach would be 2–3 km updrift (south) of the river mouths, because of the considerable natural loss of beach material from abrasion. Such effects suggest that for every tonne of gravel extracted from just south of the Rakaia River mouth, 10 t could be extracted just north of the Ashburton River mouth and 80 t from just north of the Rangitata River mouth.

SEDIMENT OUTPUT

Sediment output from the Waitaki and Canterbury beach systems is of 2 types: (1) gravel and sand that remains on the beach and accumulates along Kaitorete Barrier and at South Beach, Timaru, and (2) very fine sand and mud that accumulates in the bayheads and inlets of Banks Peninsula, on the continental shelf, and in both the Conway and Hikurangi Troughs (Fig. 1).

Kaitorete Barrier

Kaitorete Barrier is thought by Armon (1974) to have formed since the rising Postglacial sea reached present sealevel about 6500 years ago. The barrier is now 26 km long and tapers in width from 3.8 km in the north to 0.3 km in the south. The volume of the barrier is calculated from 5 equally spaced cross sections (Fig. 7, 8 and Table 6) by the End Area method (Bannister & Raymond 1972). Cross

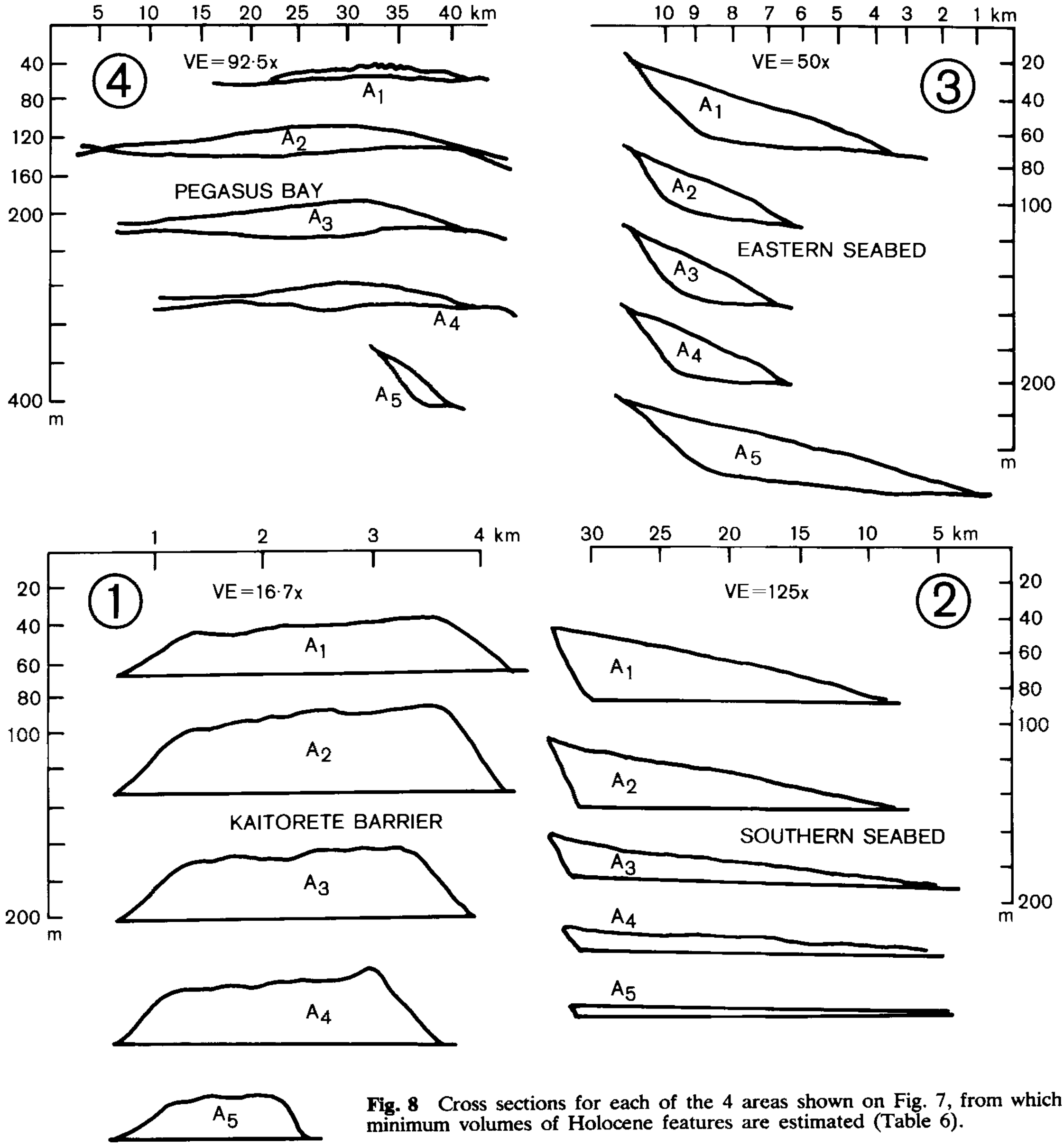


Fig. 8 Cross sections for each of the 4 areas shown on Fig. 7, from which minimum volumes of Holocene features are estimated (Table 6).

Table 6 Calculated net rates of deposition (*Qd*) around Banks Peninsula, from minimum estimated volumes (*V*) of Holocene features (Fig. 6). Kaitorete Barrier is assumed to have formed over the past 6500 years and the seabed accumulations over the past 11 000 years. Separation distance (*D*) is equidistant between each cross section. For all volume calculations the following formula was used: $V = D. [(A_1 + A_5)/2 + A_2 + A_3 + A_4]$.

Localities	Cross-sectional areas ($m^2 \times 10^3$) A_1	A_2	A_3	A_4	A_5	Age ($\times 10^3$ year)	*D* (km)	*V* ($\times 10^9$ m^3)	*Qd* ($\times 10^3$ m^3/year)
①Kaitorete Barrier	96	148	116	84	35	6.5	6.0	2.5	380
②Southern seabed	576	456	221	27	11	11.0	11.0	11.0	1000
③Eastern seabed	150	74	56	107	263	11.0	8.0	3.5	320
④Pegasus Bay	149	325	676	670	62	11.0	19.3	34.0	3100

sections above mean sealevel are from surveys by Armon (1970) and from NZMS 1, sheets 93 and 94, scale 1:63 360, topographic maps. Thicknesses of gravel and sand below mean sealevel are interpolated from bathymetry and from contours of the Postglacial Transgression Surface (Herzer 1977). Over the past 6500 years a minimum estimated volume of 2.5×10^9 m^3 of material has accumulated from the net northeasterly drift at a rate of 380×10^3 m^3/year (0.68 Mt/year). Surveys of the coast in 1862 and 1966 show that only the northern third of the barrier is advancing, the middle third remains static, and the southern third is retreating. According to estimates based on Herzer (1977), the thickness of gravel and sand at the northern end of the barrier is about 40 m (Gibb 1979). If we take the accreting section to be 8 km long and 40 m thick, with accretion decreasing from 0.5 m/year in the north (Armon 1970) to zero in the south, then 80×10^3 m^3/year (0.14 Mt/year) is now being added to the barrier. The present rate is about one-fifth of the 6500-year rate, of which one-half of the accumulation (0.07 Mt/year) may be sediment eroded from the southern third of the barrier. The lower transport rate may reflect either a reduction in the supply of sediment from longshore drift or increased abrasion as the shoreline of Kaitorete Barrier has realigned and is now almost parallel to the persistent southerly swell.

Of the 1.91 Mt/year of gravel and sand supplied to the Canterbury beach system, only about 0.07 Mt/year, or 4%, presently survives transport to be deposited on Kaitorete Barrier. The remainder is ground away by abrasion, as discussed previously. The percentage compares favourably with the previous value of 5% estimated from the changing proportion of the various gravel lithologies along the beach.

Banks Peninsula inlets

In January 1977, Gibb observed that the shorelines at the head of most of the inlets and bayhead beaches between Akaroa Harbour and Little Akaloa Bay (Fig. 7) were accreting. West of Little Akaloa Bay, the shorelines were either eroding or static. In Lyttelton Harbour, the westernmost inlet (Fig. 7), Bushell & Teear (1975) found that no significant sedimentation had occurred for the last 124 years, when they compared soundings from hydrographic surveys made in 1849, 1951, and 1973.

For Okains Bay (Fig. 7), Dingwall (1974) calculated a rate of accretion of 2.3 m/year for the period 1870–1970. The total length of the accreting shorelines is 2.5 km. If we assume they are accreting at about 2.0 m/year, and the sand is accumulating to a depth of 10 m, then the estimated deposition rate of sediment trapped by the inlets is 50×10^3 m^3/year (0.06 Mt/year).

For Akaroa Harbour, accumulation rates are determined by comparing soundings from hydrographic surveys made in 1840 (British Admiralty 1844) and 1952 (Royal New Zealand Navy 1954). Except near the harbour mouth, where a few soundings indicate scour of 3 m, all the changes, compared with Lyttelton Harbour, indicate shallowing, the greatest change being about 3 m. The average change in the 20 km^2 central part of the inlet, which has a smooth floor of sand and mud, is 0.92 m. The largest differences are greater than the 1.9 m spring tide range at Akaroa and therefore cannot arise from datum errors, but the average change may include a datum error. If we assume no datum error exists between surveys, and that little sediment is supplied from sources within Akaroa Harbour, then the harbour is trapping about 160×10^3 m^3/year (0.2 Mt/year) of the net northeasterly drift. In total, therefore, the inlets and bayhead beaches between Akaroa Harbour and Little Akaloa Bay could be trapping about 210×10^3 m^3/year (0.26 Mt/year) of very fine sand and mud.

The sediment load of the Waimakariri River, which flows into Pegasus Bay, has not been included in the calculations. Cochrane & Male (1977, fig. 4 and 6) and Blake (1968) show that sediment-laden water from Waimakariri River is generally confined to a coastal strip west of the area of sediment deposition considered here. The distribution of nearshore sediments (Fig. 6) and the pattern of nearshore currents support this contention.

Shelf sedimentation

Recent sediments have accumulated on the inner continental shelf (outer NTZ) around and north of Banks Peninsula, in depths generally less than 60 m, and overlie a clearly defined unconformity recognised by Herzer (1981) as the Postglacial Transgression Surface. Recent inner shelf sediments are assumed to have accumulated over the past 11 000 years, based on a radiocarbon age of 11 750 ± 250 years B.P. (NZ3897A) for a submerged shoreline at 53 m depth. The volume was calculated by the End Area method (Table 6).

Cross-sectional areas for the submarine spit across the entrance of Pegasus Bay are calculated from high-resolution, 3.5 kHz seismic profiles figured in Herzer (1977) and Herzer & Lewis (1979), surveyed from the New Zealand Oceanographic Institute vessel GRV *Tangaroa* in 1973 and 1975. The locations of the profiles are shown on Fig. 7 (after Herzer 1981, fig. 5, 7). South and east of Banks Peninsula, the seismic surveys are inadequate, hence, cross-sectional areas are estimated by comparing the projected contoured Postglacial Transgression Surface with the present-day seafloor. Both interpolated and surveyed cross sections are shown on Fig. 8.

Calculations (Table 6) suggest that over the past 11 000 years an estimated minimum volume of 4.9 $\times$ 10^{10} m^3 of very fine sand and mud has accumulated on the inner continental shelf around Banks Peninsula. Of this, about 1000 $\times$ 10^3 m^3/year (1.25 Mt/year) has accumulated south of the peninsula, 320 $\times$ 10^3 m^3/year (0.4 Mt/year) to the east, and 3100 $\times$ 10^3 m^3/year (3.88 Mt/year) to form the submarine spit across the entrance to Pegasus Bay.

Our study has revealed that Banks Peninsula is acting as a massive groyne, blocking all the northeasterly bedload transport of sand and gravel in the inner NTZ and partially blocking the northeasterly drift of both suspended load (mud) and bedload (very fine sand) in the outer NTZ. Quantities of very fine sand and mud that do pass northwards are deflected offshore parallel to the Pegasus Bay shoreline to form a submarine spit, the very fine sand settling out first (Fig. 4) as it bypasses the peninsula.

Trough sedimentation

About 6 Mt/year of suspended sediment are trapped in and around Banks Peninsula, less than one-half the direct river suspended load shown in Table 3. Of the difference, part is transported offshore beyond the outer NTZ to be deposited on the middle and outer Canterbury continental shelf (Herzer 1979), and part is moved northward beyond Pegasus Bay, as shown by LANDSAT II imagery (Fig. 3). Only the coarsest part of the north-going load settles on the growing submarine spit across the bay.

Muds carried in suspension past Banks Peninsula are joined by suspended load from the rivers north of Waimakariri River, such as the Hurunui (0.8 Mt/year) and the Waiau (3.7 Mt/year) (load estimates from Thompson & Adams 1979, table 3), and the Ashley, Kowai, Waipara, and Conway Rivers, for which no load estimates are available. The continental shelf between northern Pegasus Bay and the Conway Trough (Fig. 1) is not a depositional area for the mud, but is most probably a conveyance zone, as the shelf is dominantly gravel (Cullen & Gibb 1966) and in places is known to be eroding (Carter et al. in press). Part of the suspended mud conveyed northwards along the shelf is deposited in Conway Trough at rates that may be as high as 1.7 m/1000 years (Carter et al. in press). The rest is transported into Hikurangi Trough, either via the Pegasus and Kaikoura Canyons (Fig. 1), or directly across the shelf edge between them.

The head of Pegasus Canyon lies about 40 km from the present shoreline. During low and intermediate Last Glacial eustatic sealevels, the canyon trapped sand and gravel transported from the south by shelf and longshore currents (Herzer 1979). According to Herzer & Lewis (1979) it intercepts mainly north-going palimpsest sediment today; the present current regime is such that muds in suspension are probably carried northward across the canyon. It seems unlikely, therefore, that Pegasus Canyon is a significant trap for the present suspended load.

By comparison, Kaikoura Canyon, which drains Conway Trough, approaches to within 2 km of the present shoreline (Fig. 1) and acts as a conduit for dense sediment-laden water from the south, feeding the Hikurangi Trough (Carter et al. in press). A great thickness of Plio-Pleistocene sediments along the axis of the 3 km deep Hikurangi Trough is evidence of persistent sedimentation. From airgun seismic reflection profiles made by Mobil Oil and figured by Katz (1974), Adams (1980) calculated a depositional rate within the trough of 90 ± 20 Mt/year for the last 2.5 million years, of which 30–50% may be from the eastern South Island of concern here, and the remainder from Cook Strait (Lewis 1979) and other east coast sources north of Pegasus Bay. Sedimentation rates are probably lower today than during periods of lower glacio-eustatic sealevels, because fine sediment is now being deposited on the shelf, and in shelf basins like the Conway Trough, which would otherwise be funnelled into Hikurangi Trough.

SEDIMENT BUDGET AND CONCLUSIONS

The sediment input and output rates discussed above are summarised as a budget in Table 7. Both the suspended load and bedload are budgeted separately, with the mud produced by abrasion of the gravel being added to the suspended load.

The budget for the bedload is roughly in balance, with abrasion accounting for most of the input. However, the budget for the suspended load suggests that 11 Mt/year is moved out of the Canterbury NTZ eastward onto the middle and outer continental shelf and northward into the Conway Trough, and into the Hikurangi Trough via the Pegasus and Kaikoura Canyons. We have no direct measurements that would confirm this mass transfer, but the estimated value of 11 Mt/year is likely to be a minimum since no account has been taken of the abnormal load (c. 14 Mt/year) discussed earlier. Hence, at present, 25 Mt/year of river load may reach the Conway and Hikurangi Troughs. During glaciations, when the lakes of the Waitaki River system would not trap sediment (currently they trap 18 Mt/year; see Adams 1980) and when shelf sedimentation (6 Mt/year; this paper) would be negligible, the 25 Mt/year amount would be

Table 7 Sediment budget for the Waitaki and Canterbury systems. All values are in Mt/year and most are rounded to 2 significant figures. Plus sign indicates sediment input, and minus sign indicates sediment output. Suspended load includes very fine sand and mud; bedload includes fine, medium and coarse sand, and gravel. Volumes are converted to masses by assuming densities of 1.25 t/m^3 for suspended load and 1.8 t/m^3 for bedload.

	Bedload	Suspended Load
WAITAKI SYSTEM		
River input	+0.22	+1.9
Cliff input	+0.60	+0.10
TOTAL:	+0.82	
Gravel accumulated at Oamaru	-0.002	
Gravel lost by drift northward past Timaru	-0.11	
Inferred gravel loss (87%) by abrasion	-0.71	+0.71
	0.0	2.7
Inferred loss northward by drift on shelf		-2.7
		0.0
CANTERBURY SYSTEM		
Drift from south	+0.11	+2.7
River input	+0.91	+12.3
Cliff input	+0.89	+0.03
TOTAL:	+1.91	
Gravel accumulated on Kaitorete Barrier	-0.14	
Inferred gravel loss (93%) by abrasion	-1.77	+1.77
	0.0	+16.8
Sand and mud deposited in Banks Peninsula inlets		-0.26
Sand and mud deposited on shelf near Banks Peninsula including Pegasus Bay		-5.5
Inferred loss eastward to mid and outer Canterbury shelf and northward into Hikurangi Trough		-11.0
BALANCE:		0.0

increased by 24 Mt/year. The total (50 Mt/year) is about one-half the estimated 90 ± 20 Mt/year deposited in Hikurangi Trough.

Seismic profiling and bottom sampling of the continental shelf between Pegasus Bay and Kaikoura Peninsula, and of the Conway and Hikurangi Troughs, would establish the northward dispersal pattern and depositional rate of the suspended sediment that leaves the Canterbury system.

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