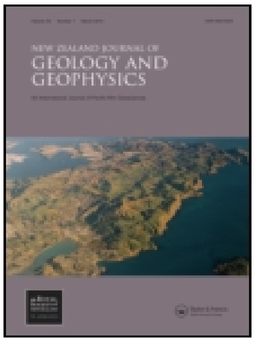

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Dual sand sources on Farewell Spit intertidal sand flats, New Zealand: partitioning during redistribution

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Abstract Extensive intertidal sand flats (c.10 000 ha, c. 100 km^2) on the sheltered southern side of Farewell Spit, a 30 km long sand spit located at the northern tip of South Island, New Zealand, extend for up to 8 km into Golden Bay. They consist primarily of fine sand with an upper size limit of 0.36 mm, blown from the spit during northerly storms. In parts of the flats fine sand is supplemented by significant but highly variable amounts of coarse sand, with rare stones up to 40 cm long. Tree trunks with tangled root masses, stranded on the flats, suggest that the coarse sediment is being delivered in the root masses of trees which are washed out of rivers discharging into Golden Bay from the mountainous southern hinterland. The greatest concentrations of coarse sediment are located northeast of the Aorere and Takaka Rivers, the two largest rivers discharging into Golden Bay. We propose that some trees are blown by prevailing southwesterly winds from the river mouths to the sand flat, and that a clockwise tidal current gyre carries trees from all rivers onto the flats in the northwestern corner of the bay. The patchy distribution of coarse sand on the intertidal flats indicates that redistribution of sand across the flats is partitioned: coarse sand (>0.5 mm) is not widely mixed with fine sand by surface processes, while fine sand is widely distributed. The sand flat extends subtidally to the 10 m bathymetric contour, giving the system a total area of c. 200 km^2. An estimated volume of Holocene age sand in the spit and the sand flats of c. 5.7 km^3 represents only c. 10% of the sand delivered to the northern tip of the South Island by longshore movement up the West Coast. The bulk of the sand may be accumulating on the continental shelf.

Keywords intertidal sand flat; Farewell Spit; Golden Bay; New Zealand; mixed sand populations; sediment delivery by floating trees; sand partitioning

INTRODUCTION

Farewell Spit is a 30 km long sand spit that extends eastward and southeastward from the northern tip of the South Island of New Zealand, across the entrance to Golden Bay (Fig. 1, 2). It is located where a regime of strong northeastward longshore movement of sand, driven by the prevailing southwesterly winds and swells of the Tasman Sea, reaches the wide western mouth of Cook Strait. Wave systems are refracted to the east and have built the E–ESE-trending spit.

Longshore movement of sand taps most of the West Coast of the South Island, north of the southwestern fiords. This comprises >500 km of rugged coastline, backed by the Southern Alps (altitude up to 3764 m, Mt Cook/Aoraki) (Fig. 1). Orographic rainfall is high, west-facing slopes are steep, and river flows and sediment delivery to the coast are substantial. The system delivers an estimated 5–6 million m^3/yr of sand (Furkert 1947; van der Linden 1969), though van der Linden noted that this may be an underestimate.

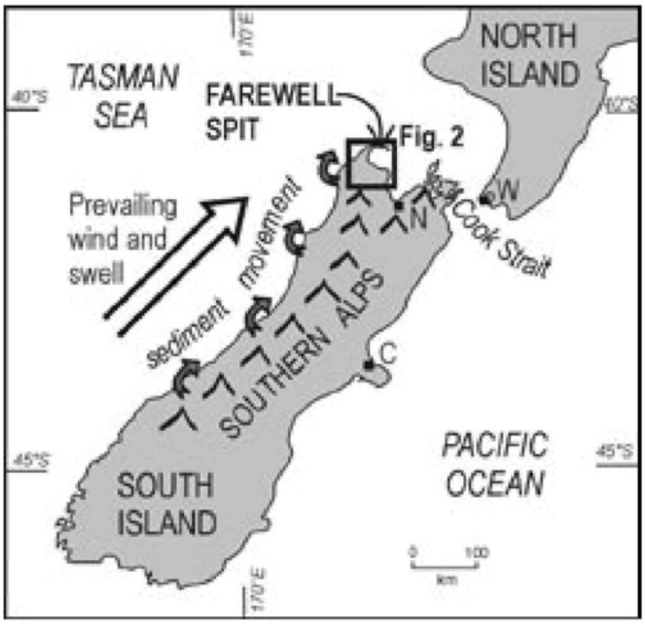

Fig. 1 Location of Farewell Spit in relation to longshore sand supply and Cook Strait, New Zealand. C = Christchurch, N = Nelson, W = Wellington.

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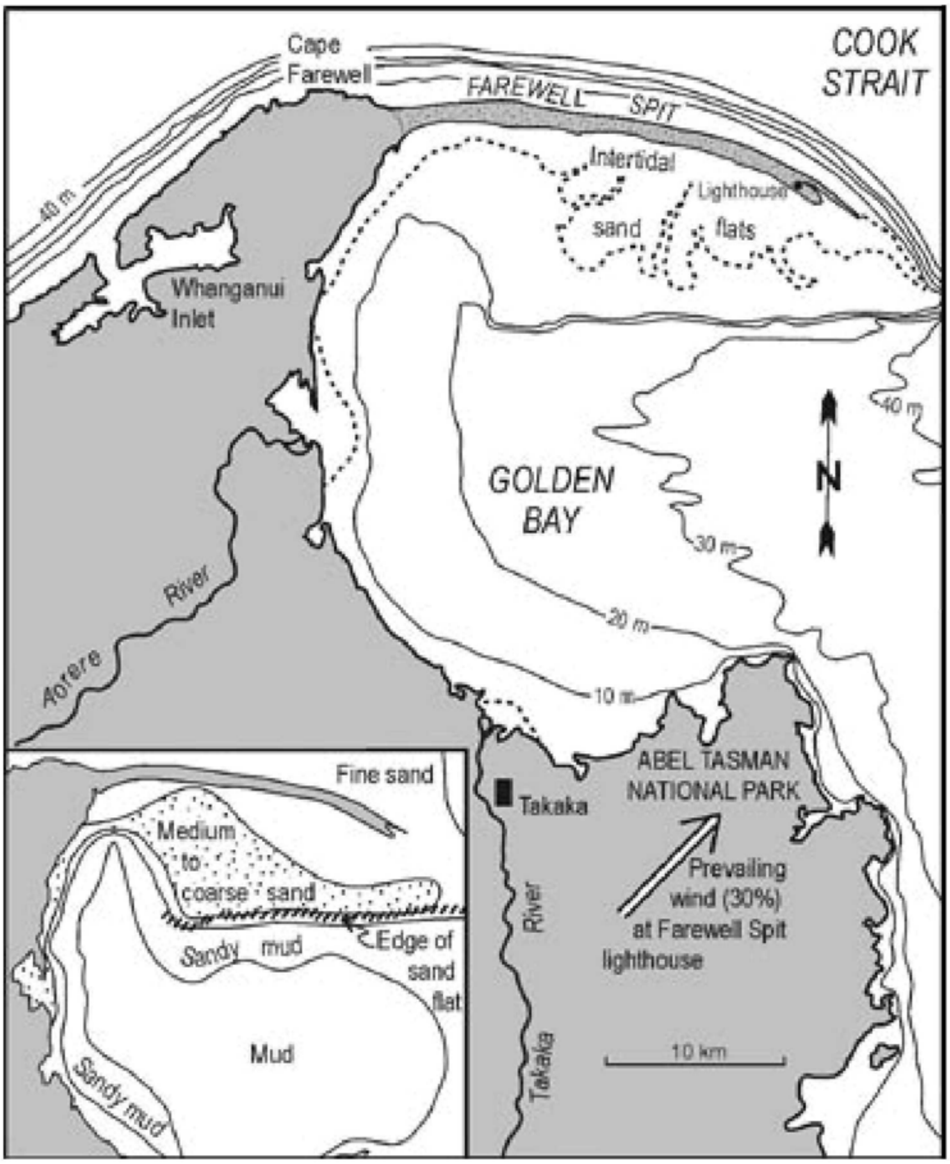


Fig. 2 Golden Bay area, northwestern South Island, showing Farewell Spit and the intertidal sand flats, with the major ebb-tide drainage channels and low-tide position (dashed line). Bathymetric contours (metres) in Golden Bay from Rattenbury et al. (1998). The submerged foreset face of the sand flat is shown by the east–west line of the 10 and 20 m contours. Prevailing wind direction at Farewell Spit Lighthouse from Sevon (1966). *Inset*: van der Linden's (1969) sediment map.

The spit presumably has a complex Quaternary history of degradation during glacial low sea levels and reconstruction during interglacial high sea levels. However, the present form of the spit is entirely of Holocene origin. It comprises a smoothly curving convex ocean beach, facing north and backed to the south by mobile sand dunes up to 22 m above sea level. The spit is 30 km long and c. 1 km wide and is actively extending southeastwards. South of the subaerial spit, extending into the sheltered waters of Golden Bay, a wide intertidal sand flat ranges in width between 2 km at the extremities of the spit, and >7 km in the central part, an area of c. 100 km^2. It is actively extending southwards into the bay, approximately to the 10 m bathymetric contour (Fig. 2), giving a total area of sand accumulation of c. 200 km^2. The intertidal flats are clearly visible from space, and are the only intertidal structure shown on the 1:1 000 000 map of the South Island.

This study focuses on the intertidal sand flats, and concludes from a comprehensive grid of samples that fine to medium sand (<0.36 mm), which has long been recognised as blown from the spit by northerly storm winds, is supplemented by significant but highly variable quantities of coarser material (>0.36 mm) brought from the hinterland of Golden Bay in the roots of floating trees.

PREVIOUS WORK

Sevon (1966) examined grain size and mineralogy of Farewell Spit sands from 10 transects (foreshore-backshore-dune) on the northern (ocean) side, and 5 transects (dune and nearshore tidal flat) on the south side, a total of 40 samples. Sevon was followed by van der Linden's ship-based study (1969) of sediments of the continental shelf and Golden Bay, and M. R. Gregory's unpublished study of the coastal sands of Golden Bay and Farewell Spit (in Bergquist et al. 1975). All workers found that the ocean beach and dune sands have uniform size characteristics, being very well sorted with a mean grain size of c. 0.2 mm. Sevon (1966) noted that ocean foreshore sand is slightly coarser grained (mean size 0.2–0.25 mm), less well sorted, and more variable than backshore/dune sand (mean size 0.17–0.2 mm), and that it shows a slight tendency to increase in size towards the east, whereas backshore/dune sand retains a more uniform size.

On the intertidal flats, Sevon (1966) and Gregory (in Bergquist et al. 1975) found nearshore sands to be more variable in size distribution, with rare samples being coarser grained and less well sorted. Most samples, however, were identical to the adjacent dune sands. Van der Linden's (1969) Golden Bay suite of 52 subtidal samples was spaced uniformly and widely across the bay, and included 15 on the sand flat and its subtidal extension to the 10 m contour. He noted an east–west band of coarser (mean size up to 0.44 mm) and less well sorted sand forming the southern edge and immediate subtidal extension of the flats, to a depth of c. 10 m. At greater depths, bottom sediment fines to mud. The sand flat is widest adjacent to the central and eastern parts of Farewell Spit, and is separated from the western coastline of Golden Bay by a deep channel (>10 m) containing muddy sediment (Fig. 2).

SETTING

Water circulation in Golden Bay

The predicted diurnal tidal range on the western coast of Golden Bay varies between 1.5 and 4.8 m (neap and spring tides). Water circulation within Golden Bay, shown by drift card experiments (Heath 1969, 1973), comprises a clockwise gyre that splits from the eastward moving D'Urville Current of Cook Strait. Drift cards entering Golden Bay tend to accumulate in the northwestern corner of the bay. These two points are relevant to later discussion of movements of floating trees.

Bottom current speeds were measured by Ridgway (1977), in the middle of Golden Bay (station K51, water depth c. 27 m), and 4 km east of the tip of Farewell Spit (station K61, water depth 54 m). Both locations experienced reversing tidal flows that did not exceed 30 cm/s. This is well below the threshold of erosion and transportation of fine–medium sand (0.1–0.4 mm), which is c. 50 cm/s at 1 m above the bottom, on the curve of Sundborg (1956). We conclude that sand on and around Farewell Spit is moved by wave action, by channelled drainage on the flats, and by wind, but not by tidal currents, except perhaps locally.

Form of the intertidal sand flat

Much of the flat is planar and covered by a mat of eel grass (*Zostera*) which varies in concentration from sparse to dense. On a meso-scale (metres) the planar surface is disrupted by holes excavated by feeding eagle rays (*Myliobatus caudatus*) (Gregory et al. 1979; Hines et al. 1997). The rays jet water into the sand in order to extract benthos. A well-preserved single excavation is circular, vertical-sided, 15–50 cm in diameter, and up to 20 cm deep. Commonly, recent excavations are concentrated along the margin of a composite excavation, where feeding rays are extending their activities into a *Zostera*-covered flat. Composite excavations give rise to pools of standing water 10–20 cm deep and up to several metres across.

On a macro-scale (tens to hundreds of metres) the flats are cut by substantial channels along which draining tidal water is concentrated. Some of these could not be crossed safely by our foot parties. Major channels are shown on Fig. 2.

Volume of sand

Bathymetric contours (Fig. 2) indicate that the sand flat has been built out to c. 20 m water depth, giving a total area of c. 200 km^2. There is no drillhole or seismic evidence of the thickness of postglacial sand, but extrapolation of bathymetric contours around Golden Bay suggests a mean thickness of c. 20 m, giving a volume of c. 4 km^3 of sand forming the sand flats. By similar reasoning, Farewell Spit itself contains c. 1.7 km^3 of sand, giving a total of c. 5.7 km^3 of postglacial sand in the Farewell Spit system.

Estimates of annual delivery of sand to the vicinity of Farewell Spit from longshore movement (Furkert 1947; van der Linden 1969) are in the order of 5–6 million m^3/yr (0.005–0.006 km^3). Maintained for 10 000 yr of Holocene time, that rate would have delivered 50–60 km^3 of sand. It thus seems that the Farewell Spit system contains only about one-tenth of the sand moved up the West Coast in postglacial time. There are several possible explanations for the discrepancy. First, estimates of present-day movement are subject to many uncertainties and may be wrong. Second, van der Linden (1969) noted that sand thicknesses on the continental shelf northwest of the northern South Island require an annual sand delivery considerably greater than 5 million m^3. Thus, partitioning of sand between the spit and the shelf may be unequal, the majority of sand remaining on the shelf. Third, nearshore sand may be bypassing the spit and moving on into Cook Strait. However, bathymetric contours suggest that the sand platform extends only c. 7.5 km beyond the subaerial spit. A rapid drop-off to water depths >20 m (Fig. 2) does not suggest that significant quantities of sand are moving beyond the platform.

THE PRESENT STUDY

The present study is adjunct to a biological survey of the intertidal sand flats (Battley et al. 2004), organised by the Ornithological Society of New Zealand, and funded by the New Zealand Ministry of Fisheries. It was intended to identify and quantify benthic food sources for migratory and non-migratory wading birds, for which Farewell Spit and the sand flats have been an internationally renowned sanctuary since 1938.

With the field assistance of 20 students from the 2003 class of the New Zealand Department of Conservation Trainee Rangers course at Nelson-Marlborough Institute of Technology, and several volunteers, a grid of 190 stations was sampled (Fig. 3). North–south transect lines were spaced at 1 km intervals, along New Zealand Map Series kilometre grid lines, and samples were taken at half-kilometre intervals (with alternate sites located on New Zealand Map Series east–west kilometre grid lines) along each line, from the edge of the vegetated salt flat to the farthest practicable point at low tide. Most sampling was done on foot. Positioning by Global Positioning Satellite had a margin of error of ±5 m.

In addition to biological samples, a 10 cm core of sand was taken at each sample location. The surface layer of oxidised sand varied in thickness, but was generally less than the depth of the core. No internal variation was noted in the sand cores. 188 sand samples were finally available for analysis.

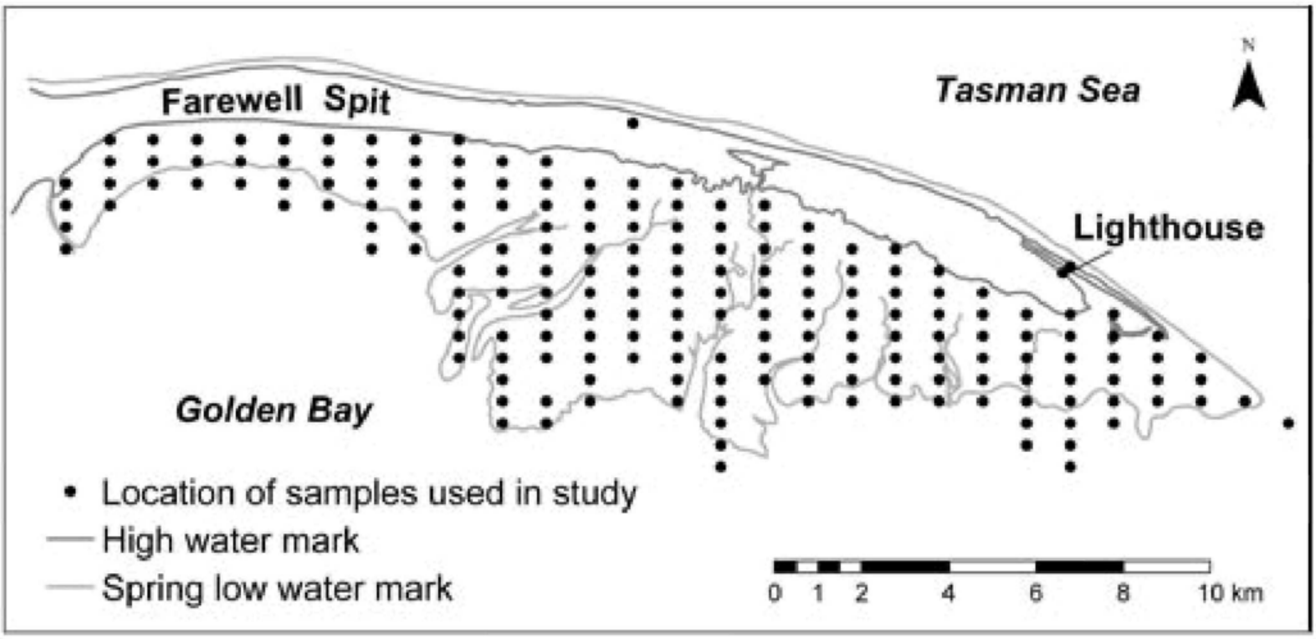


Fig. 3 Sampling sites for this study, including three on the ocean beach and sand spit. The remaining sites are on the intertidal sand flat. Where sample lines extend beyond the mapped low-tide line, that is an indication of the continuing southwards extension of the flat. North–south transect lines (New Zealand Map Series kilometre grid lines) were labelled from west to east: A, AA, B, BB, C, CC etc. East–west sample lines follow NZMS kilometre and half-kilometre grid lines. The northernmost sample line is mid-way between the 77 and 76 northing grid lines, Map Sheet N24.

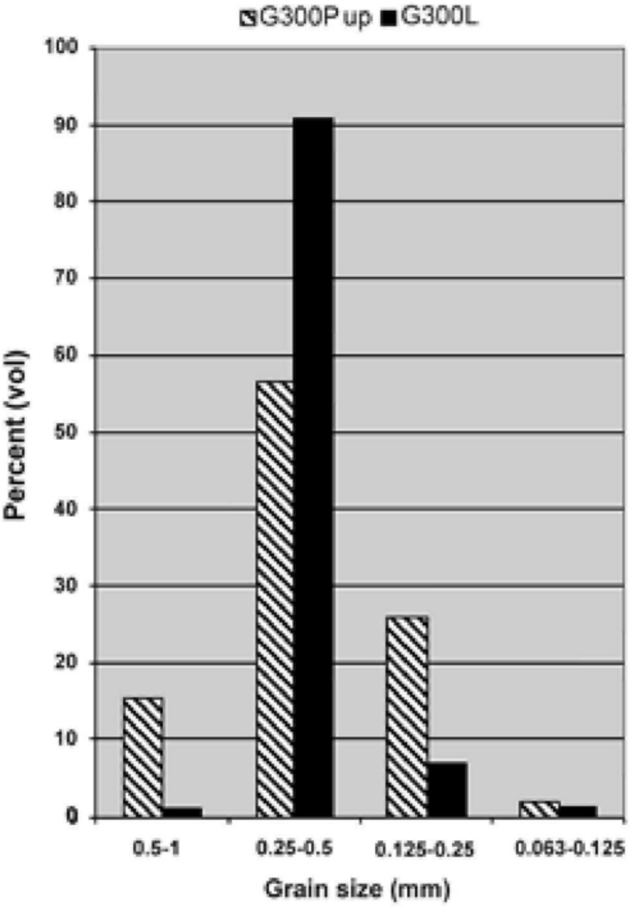


Fig. 4 Comparison of two field grain-size analyses, of samples taken by different field parties from the same sample location (±5 m).

SAND METHODOLOGY

In order to handle the large number of samples, an experimental field procedure was devised for wet-sieving sand at two base camps, using 10 cm diameter stainless steel sieves with mesh sizes at 1, 0.5, 0.25, 0.125, and 0.063 mm (the whole-phi divisions 0 to +4 of the Wentworth size scale). This encompasses all of the sand particle size divisions (2.0–0.063 mm). Sea water from hand-pumped garden spray bottles was used, and proportions measured by volume with a precision of ±2–3% (0.5 ml in a sample of 25 ml).

Problems with the field methodology

Of the 188 samples, 141 were processed during the 10 day field camp. Problems in the procedure quickly became apparent, from inter-operator variability to rapid clogging of the finer sieves. By chance, one site was visited by both field parties, on separate days (within the ±5 m spatial precision). Figure 4 shows the two independent analyses, done on different equipment, for the two samples. The results differ considerably.

Later comparison with 10 control samples, dry-sieved at Auckland University, also indicated that the field results were unreliable in most respects. In four samples with both field and laboratory sieving, dry sieving achieved a greater separation through successively finer sieves (Table 1). The control samples were therefore taken as representative of the total size distribution.

Our aim to identify possible correlations between sand size distribution and infaunal biotic distribution was thus not achieved. However, the experimental field procedure did yield two reliable results which form the basis for this paper. First, visual inspection of the 0.5 mm sieve during processing indicated that it was consistently effecting a reliable separation

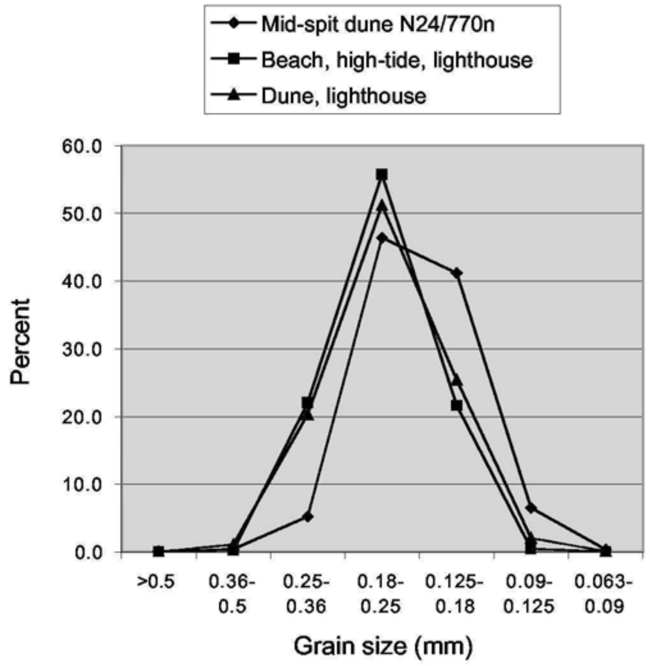


Fig. 5 Grain-size distribution of three Farewell Spit dune and ocean beach sands from laboratory sieving. The mode in each case is in the 0.18–0.25 mm size interval, but there is variation in detail. There is very little sand coarser than 0.36 mm. Sample locations shown on Fig. 3. Table 2 shows the Folk numerical summary for all 10 laboratory-analysed samples.

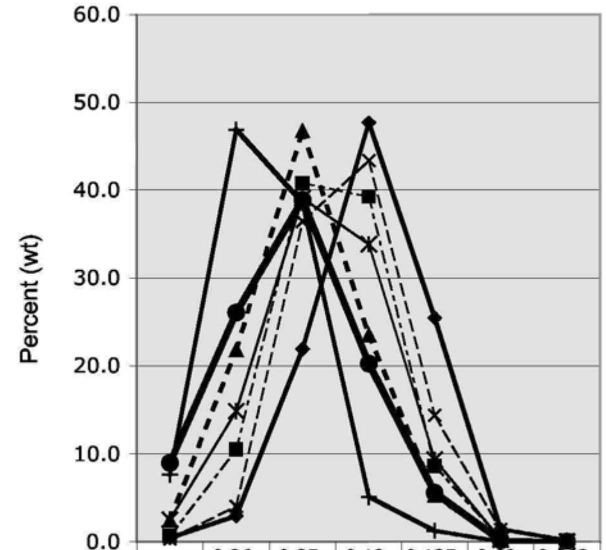
of the coarse sand fraction, regardless of inefficiencies in the finer sieves. As a consequence, following the field camp the remaining 47 samples, plus 3 already-analysed samples that had been retained, were washed through the 0.5 mm sieve only, in order to obtain the volume percent sand >0.5 mm. The sand held on the 0.5 mm sieve was closely scrutinised in these later analyses, and while most had only a trace, others had amounts up to 42%. Second, material passing the finest sieve (mud) was absent to negligible in all field and control analyses.

RESULTS

Comparison of sand flat and beach dune sands

Ocean beach sands and sand-spit dune sands analysed among our control samples are shown in Fig. 5. As found by previous investigators, the sands have a mode (highest point in the grain-size curve) in the upper fine sand division, 0.18–0.25 mm, and have negligible material coarser than 0.36 mm. This sand has always been regarded as the primary source of sand on the sand flats, because the dominant storms are northerly, and because many residents and visitors on the sand spit have seen sand blowing from the dunes onto the flats.

Using laboratory-sieved samples only, comparison of dune sands with sand flat sands (Fig. 6 and Table 2) shows that all sand flat sands are significantly coarser grained. Even if the mode is the same (e.g., FF350), the sand flat curve is skewed towards coarser grain sizes. There is a significant component coarser than 0.36 mm (the maximum size in dune sands) in all sand flat samples analysed.



	0.5-1	0.36-0.5	0.25-0.36	0.18-0.25	0.125-0.18	0.09-0.125	0.063-0.09
FF350	0.4	2.9	21.9	47.7	25.4	1.4	0.2
H100	0.6	10.4	40.7	39.3	8.6	0.3	0.0
HH150	2.5	21.8	46.8	23.5	5.3	0.1	0.0
II350	0.3	4.0	36.4	43.4	14.4	1.4	0.2
LL606950	2.5	14.8	39.1	33.9	9.4	0.2	0.0
N050	9.0	26.1	38.9	20.3	5.6	0.2	0.0
O000	7.7	46.9	38.6	5.1	1.2	0.0	0.0

Grain size (mm)

Fig. 6 Grain-size distribution for the seven laboratory-analysed sand-flat sands. Important features are the considerable quantities of sand coarser than 0.36 mm (i.e., not derived from Farewell Spit), and the wide variation between samples. The table below the graph shows weight percentages for each sand in the different size categories along the rows, while comparison up and down columns illustrates the wide variability in weight percent in each size category.

Table 1 Comparison of field and laboratory analyses of four sand flat sands. Numbers are percent retained on the sieve (vol. % for field (F), wt% for lab (AU)). Laboratory analyses achieved better separations through nearly all sieves.

	Sieve mesh (mm)			
Station no.	0.5	0.25	0.125	0.063
H100F	1	59	39	1
H100AU	1	51	48	0
HH150F	1	75	23	1
HH150AU	3	68	29	0
N050F	13	80	6	1
N050AU	9	65	26	0
O000F	20	78	2	0
O000AU	8	86	6	0

Comparison among laboratory-sieved sand flat samples

The seven samples vary widely among themselves (Fig. 6, Table 2). Dune sand blown from the north is being supplemented on the flats by coarser sand (>0.36 mm), but to widely varying degrees.

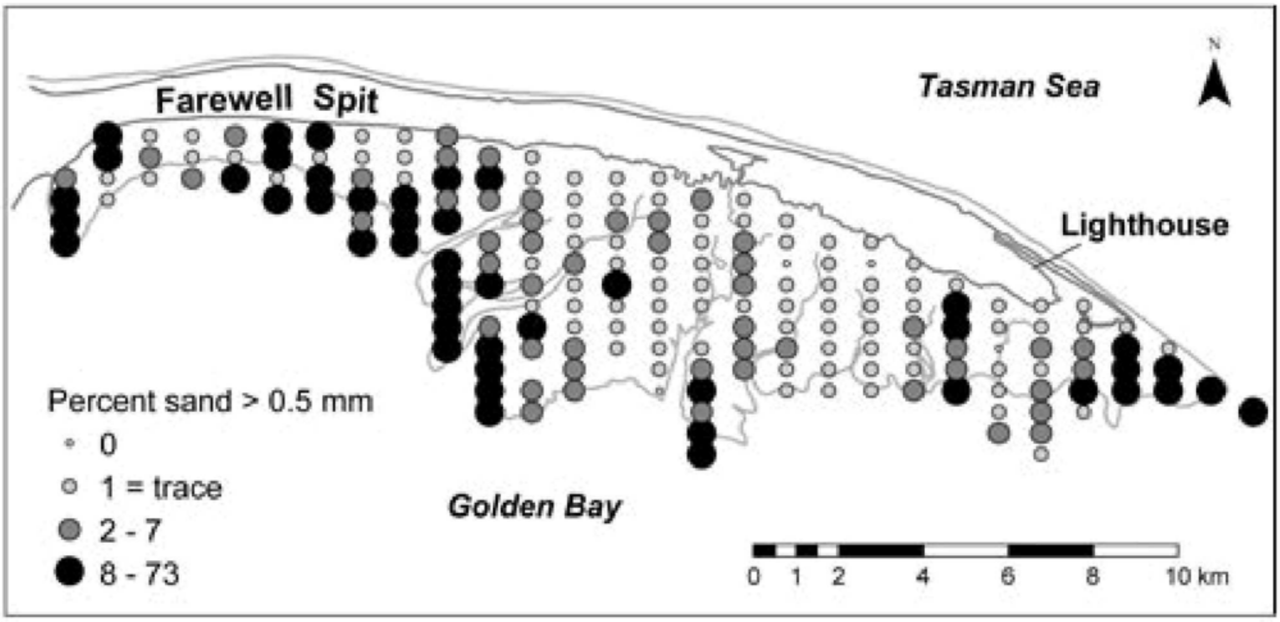


Fig. 7 Airphoto-derived map (2003) of Farewell Spit and the intertidal sand flats showing the percentage of sand coarser than 0.5 mm at each sample station (i.e., sand not derived from Farewell Spit). Coarse sand is concentrated on the eastern and western portions of the flats.

Table 2 Grain-size summary, Farewell Spit samples dry-sieved at Auckland University. Formulae of Folk (1968).

Sample station	Graphic Mean (phi units)	Sorting (inclusive graphic standard deviation in phi units)	Skewness (inclusive graphic skewness)
Mid-spit dune sand	2.22	0.37	+0.12
Lighthouse dune sand	2.05	0.42	0.0
Lighthouse beach sand	2.0	0.39	+0.02
Sand flat samples:			
FF350	2.03	0.45	–0.06
H100	1.73	0.46	+0.07
HH150	1.53	0.48	+0.1
II350	1.83	0.43	+0.15
LL606950	1.65	0.48	0.0
N050	1.43	0.55	–0.04
O000	1.2	0.41	+0.06

Mean size: 1–2 Ø = medium sand, 2–3 Ø = fine sand.
Sorting: <0.35 Ø = very well sorted, 0.35–0.5 Ø = well sorted, 0.5–0.71 Ø = moderately well sorted.
Skewness: +0.3 to +0.1 = fine skewed, +0.1 to –0.1 = near symmetrical, 0.0 = symmetrical, –0.1 to –0.3 = coarse skewed.

Sand retained on 0.5 mm sieve, field analyses

Accepting that percentage retained on the 0.5 mm sieve in the 188 field and later analyses is for the most part a reliable figure, there is wide variation. Many samples had only a trace (c. 1%), but others had up to 73% >0.5 mm (Fig. 7). In recognition of possible over-estimation of quantity in some samples, Fig. 7 only distinguishes samples with <2, 2–7, and >7% sand >0.5 mm. Sites with >2% coarser than 0.5 mm are not uniformly distributed across the flat, but are concentrated in discrete areas.

Other observations on the sand flats

Occasional stones were seen on the sand flats. They are rounded to varying extents, and range up to 30–40 cm in size. Also seen were several tree trunks with tangled root masses. The trunks had stranded on the sand flats at varying distances from the shore, and none of the root masses seen contained stones. However, the presence of stones and trunks in an environment lacking other known sources of stones gives a strong indication that stones are arriving tangled in the root masses of floating trees. By extension, we postulate that the sand fraction coarser than 0.36 mm is also arriving in tree roots.

DISCUSSION

Source of the bulk of sand-flat sand

The assumption that Farewell Spit provides a large proportion of the sand making the flats (<0.36 mm) is supported by recorded wind speeds at the Lighthouse (Fig. 8). Mean wind speed for all months except June is 20 km/h or more. For dry sand of diameter 0.2 mm, a threshold velocity of 12 km/h (measured 10 m above the surface) is sufficient to initiate movement by saltation. The ability of wind to move sand increases exponentially, approximately as the cube of the velocity (Bagnold 1941). Therefore, the normal wind regime on the spit is well above the threshold velocity, and is capable of delivering dune sand to the sand flat at all times when wind direction is suitable. The dominant storm wind for the region is northerly and delivers sand from the beach and dunes to the entire length of the sand flat.

Source of the coarse sand—floating trees?

The western and southwestern hinterland of Golden Bay is mountainous and receives high orographic rainfall (>2 m/yr). It is drained by two major rivers, Aorere and Takaka, and several lesser rivers (Fig. 2). Significant flood events occur in most years, and many floodplain trees are carried into the bay. Floating trees are frequently observed to carry soil in their root masses as they enter the sea (Jo-Anne and Alan Vaughan pers. comm. 2004). This observation supports our inference that floating trees deliver coarse sand and occasional stones to the sand flats. Flood debris from the Takaka River tends to move clockwise around Golden Bay. Trees from that river have not been observed carrying sand and gravel. Additional flood debris from rivers located east of Abel Tasman National Park (Fig. 2) is carried into Golden Bay on occasion. Much floating debris eventually strands on the beaches on the south side of Farewell Spit (G. Rennison pers. comm. 2004).

The prevailing southwesterly winds (Fig. 2) would tend to push floating trees from all rivers towards the sand flats. Those from the Aorere River would tend to strand on the western flats, and those from the Takaka River on the eastern flats. The two greatest concentrations of coarse sediment on the flats are downwind from the two major rivers. The greater concentration in the west-central region may be explained by two factors, first the shorter travel distance from the Aorere River mouth, and second the clockwise current gyre in the bay which would tend to push trees from both rivers towards the northwest corner of the bay.

Possible introduction by littoral drift

The presence of a coastal strip of coarser sand extending from the mouth of the Aorere River into the northwest corner of Golden Bay (Fig. 2 inset) raises the possibility that littoral drift processes may be responsible for moving coarse sand around the corner and onto the flats. However, the distribution of coarse sand suggests that this is not happening to any significant degree: Fig. 7 shows that there is no nearshore continuum of coarse sand, and that most of the coarse sand is on the outer and most distant parts of the sand flat. Similarly, the stones are found on distant parts of the flats. The east-central region of the sand flats is deficient in coarse sediment.

Movement of sand on the flats

Sand is being spread over an area of c. 200 km^2. Several processes have the potential to move sand around on the flats. They include ebb and flow of the diurnal tides, in association with widely varying wind and wave conditions. Sand on the flats dries sufficiently during the intertidal cycle for wind to blow it around (pers. obs.).

In a sheltered, inner harbour setting, on an intertidal sand flat composed of well-sorted very fine sand (0.063–0.125 mm—i.e., finer than our sands), Bell et al. (1997) showed that sand movement could not be initiated by peak tidal flow alone, but that tidal flow in combination with near-bed orbital currents generated by small wind waves was able to initiate sand transport. There are no measurements of tidal current flows in the intertidal environment at Farewell Spit, but given the coarser sand, and the inability of tidal flows in deeper water to move the sand, a similar combination of tide and wave action is likely to be needed to move fine sand on the Farewell Spit sand flats.

The ebb-flow rivers in major channels on the flats move much sand seawards, while the steep, submerged, southern margin of the flats (10–20 m water depth) indicates that sand is moving and building southwards in a deltaic topset–foreset fashion. The planar surface of the sand flats is the analogue of a delta topset surface.

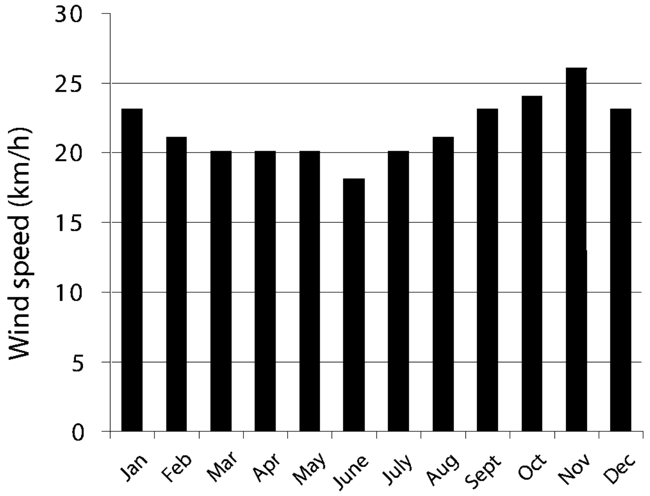


Fig. 8 Average monthly wind speeds recorded at Farewell Spit Lighthouse (New Zealand Meteorological Service 1980).

Partitioning of sand movement

Despite the fact that sand is being spread apparently uniformly across c. 200 km^2 of sand flat (including the subtidal part), the observed irregular distribution of coarse sand (>0.5 mm) on the intertidal flats (Fig. 7) shows that there is no widespread mixing of it. We conclude that tidal, wind, and wave action on the sand flats does not move the coarse sand over significant distances, that is, sand movement on the flats is partitioned. Fine sand, in contrast to coarse sand, is moved and homogenised by a combination of waves, wind, tidal ebb and flow, clockwise current gyre, and drainage channels across the entire flat.

Isolated stones—drop stones

Isolated drop stones are found in many otherwise fine-grained marine sedimentary rocks. Sources of such stones are known in floating ice (extensively documented), floating trees, and as gizzard stones in some marine mammals. Flotation has also been noted as a mechanism of transporting drop stones (Hume 1964).

Floating trees are not well documented. Ballance (1988) recorded abundant drop stones, several to the square metre, reaching 15 cm in size, in some continental shelf mudstones offshore of a major, vegetated, braidplain delta. Floating trees were thought to be the most likely method of delivery.

Flotation of sand and small pebbles occurs as a surface tension phenomenon in rising and moving water that is calm, chiefly in estuaries or among floating ice (Hennesey 1871; Hume 1964; Syvitski & van Everdingen 1981). The sand must be clean and dry, and can either be lifted by gently rising water, or can float after falling into calm water from heights of up to 250 mm (Hume 1964). Tabular or disc-shaped grains float better than spherical. The theoretical maximum size of pebble that can be supported is 11.7 × 7.8 × 2.0 mm, for chert of density 2.7, in sea water at 0°C (max. surface tension) (Hume 1964). Hennesey (1871) noted floating pebbles, with dry upper surfaces, which were "nearly as broad and a little thicker than a four penny piece". The English four penny piece (the groat), nineteenth century version, was 16 mm in diameter (Royal Mint Museum to DSM pers. comm. Feb 2004). Thus, Hennesey's pebbles were of a similar size to the calculated maximum pebble.

In relation to the Farewell Spit flats, it is unlikely that coarse sediment could float from the Golden Bay rivers across the open waters of Golden Bay without disturbance of the surface tension. The larger stones seen are far too big to float, anyway. However, once deposited on the intertidal flat, both fine and coarse sand and small pebbles could be redistributed shorewards by flotation on the rising tide on calm days. Syvitski & van Everdingen (1981) concluded that, in Boundary Bay on the Fraser River delta, Canada, floating sand patches travel on average 10 m shoreward on each tidal cycle, and that homogeneous sand size distribution across the intertidal flats is probably a consequence of redistribution by flotation. They calculated a critical velocity for 0.5 mm grains of c. 10 cm/s, above which all grains would sink. They noted that floating sand coming into contact with eel grass (*Zostera*) sinks because the grains pile up and exceed the critical weight. On Farewell Spit, this process (if it occurs—it has not been recorded) would tend to concentrate sand accumulation on *Zostera*-covered areas.

Other mechanisms for transporting coarse sand

Floating mats of vegetation or seaweed might also convey coarse sand to the sand flats. However, they could probably not carry stones, except attached to kelp holdfasts, and they would not normally have an inbuilt source of sand in the way that trees undermined on flood plains do. Seaweed is not conspicuous in Golden Bay, and in particular oceanic kelp is absent. Flood debris from the rivers does include leafy vegetation, but there are no reports of such debris carrying sand or stones.

Mud

The effect of *Zostera* cover on the intertidal and immediately subtidal accumulation of fine sediment has been studied in Otago Harbour, New Zealand. Heiss et al. (2000) measured significantly lower and less variable tidal current velocities inside a patch of 12 cm tall *Zostera* than above and around it. The effect of this on accumulation of mud (grains <0.063 mm) was to allow greater concentration inside the *Zostera* (1.1% of the accumulating sediment) than around it (0.4%). Mud is accumulating in deeper parts of Golden Bay (Fig. 2), and there is a supply of mud from the hinterland. However, on Farewell Spit we noted only rare traces of fine sediment (some of which could have been decaying organic matter). Mud is either not reaching or is bypassing the intertidal sand flats. The clockwise current gyre would tend to move suspended mud from river mouths onto the flats. Thus, threshold water velocities exceeding those for mud transport (c. 2 cm/s) are indicated across the flats.

CONCLUSIONS

The intertidal sand flat on the sheltered southern side of Farewell Spit (100 km^2) consist primarily of fine sand from the ocean side of the spit (<0.36 mm) blown from the spit during northerly storms. In parts of the flats, fine sand is supplemented by significant but highly variable amounts of medium to coarse sand (>0.36 mm), and rare stones up to 40 cm long. The presence of tree trunks with tangled root masses, stranded on the flats, suggest that the coarse sediment is being delivered in the root masses of the trees, which are washed out of flooded rivers discharging into Golden Bay from the mountainous southern and western hinterland. Local observers report that this is a frequent occurrence. The greatest concentrations of coarse sediment are located northeast of the mouths of the two largest rivers discharging into Golden Bay. We propose that trees are blown by prevailing southwesterly winds from the river mouths to the sand flat. A clockwise tidal current gyre may carry trees from all rivers onto the northwestern flats.

All mud is winnowed from the sand flats by wave and tidal action. Fine sand is moved around sufficiently to build a flat delta-type accumulation covering 200 km^2, with a steep foreset face at 10–20 m water depth. Coarse sand, however, is not mixed and homogenised across the flats. Farewell Spit intertidal sand flats thus comprise sand from two contrasting sources (<0.36 mm and >0.36 mm), which remain partitioned according to grain size during sand redistribution on the flats. The floating tree delivery of coarse sediment that we infer is a novel mechanism that has not been widely reported.

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