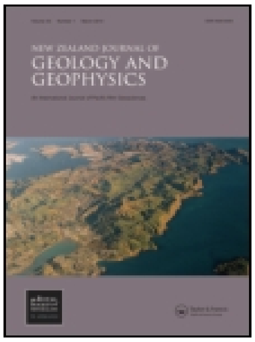

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SEA-LEVEL FLUCTUATIONS CAUSE PERIODIC, POST-GLACIAL PROGRADATION, SOUTH KAIPARA BARRIER, NORTH ISLAND, NEW ZEALAND

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ABSTRACT

The off-shore region between Mt Egmont and the Kaipara Harbour entrance forms the off-shore portion of the **Egmont–Kaipara Sand System.** The late post-glacial input of sand from landward sources into this system is less than 7% of the volume of post-glacial dunes which forms its coastal deposits. The only other source for the dune sand is the sea floor. Hence it is not surprising that the mineralogy of the sea floor and dune sands is the same. Furthermore, five separate periods of progradation are recognised that are correlated with five periods of sea-level fluctuations which have occurred during the post-glacial fall in sea-level from a local maximum of +2·1 m, 4425 years ago. The volume of progradation is approximately proportional to the net fall in sea level during each fluctuation. Departures from this proportionality are due mainly to insufficient time for equilibrium to be established between sea floor and new sea level. Sea level is currently rising and is promoting deposition on the sea floor down to depths of 50 m, beyond which there is a belt of coarser sand down to an average of 100 m. The main movement of sand is between the depth of 50 m and the shore. A wedge of sand from this region with a maximum, near-shore thickness of 2·1 m (the overall post-glacial fall in the sea level) equals slightly more than the total volume of post-glacial dune sand preserved within the Egmont–Kaipara Sand System. It is concluded that the present sea floor is in partial equilibrium with sea level, and the local profile of equilibrium probably extends to depths of between 80 and 120 m.

INTRODUCTION

Post-glacial progradation along the west coast of South Kaipara Barrier, north-west of Auckland, consists of a magnificent belt of post-glacial dunes 3·5 km wide by 50 km long. Brothers (1954) described these in detail, concluding that there were three main belts, representing three main periods of progradation separated by periods of retrogradation. Although Brothers recognised that the post-glacial fall in sea level was an important factor controlling dune formation, he was unable to explain "the intervention of two erosional periods" and thus considered that some form of climatic control had been effective. However, it has since been shown that the post-glacial sea level has fallen in a fluctuating manner so that periods of transgression which promote erosion (Bruun 1962; Schwartz 1965) would have interrupted periods of regression which promote progradation. Local evidence for a fluctuating post-glacial sea level is given by Schofield (1960) who showed that for the Firth of Thames region, overall sea-level fall was 2·1 m during the last 4425 years. This fall and attendant fluctuations apply to the whole of the Northland and Auckland regions (Schofield 1973) and at Mangatawhiri Spit has resulted in an off-shore derivation for the sand

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(Schofield 1967a). The recognition of five periods of progradation for the post-glacial coastal dunes of the South Kaipara Barrier permits a more detailed assessment of the results of this sea-level fall.

DUNE BELTS

Description

Five distinct dune belts of Holocene age are recognised along the South Kaipara Barrier (Figs 1, 2).

Dune Belt 1 (oldest)

Dune Belt 1 consists of almost wholly vegetated, parabolic dunes (Fig. 2) rising to over 180 m. These have buried a high coastal cliff and a hinterland of more highly weathered and cemented Pleistocene dune sands.

Dune Belt 2

Dune Belt is much narrower than Dune Belt 1 but is similar in its almost complete cover of vegetation and parabolic dune formation. It rises to over 60 m above sea level. Brothers (1954) included both Dune Belts 1 and 2 in his Group I, but aerial photos (e.g., Fig. 2) show that Dune Belt 2 is clearly separable from both Dune Belts 1 and 3. The contact between Dune Belts 2 and 3 is characterised by many lakes, a feature also present to a lesser extent along the contact between Dune Belts 1 and 2.

Dune Belt 3

Dune Belt 3 is also primarily formed of vegetated parabolic dunes but much of its surface (Fig. 2) is covered by a mixture of blow-out dunes and younger transverse dunes that advanced over Dune Belt 3 not long before or during the formation of Dune Belt 4.

Like Dune Belt 1, Dune Belt 3 widens considerably at its northern end where it also extends out into the ocean as a subsidiary spit separated from the main barrier by Waionui Inlet (Fig. 1). At its wider northern end it is generally less than 30 m high but commonly rises to almost 60 m to the south-east, within its greater, narrower length.

Dune Belt 4

Unlike the older dune belts, Dune Belt 4 is an almost entirely non-vegetated belt of transverse dunes (Fig. 2). It is easily separated from Dune Belt 3 in the north but probably buries southern portions of Dune Belt 3. Over large portions of its length (Fig. 1) Dune Belt 4 is sub-dividable into two separate phases of transverse dune formation, both of which rise to 55 m above sea level.

Dune Belt 5

Dune Belt 5 is the latest to be formed and rises to 24 m above sea level. It is quite distinct in form from Dune Belt 4, and consists of partially vegetated, irregularly-surfaced foredunes which become more parabolic in form southwards. Transverse dunes are absent.

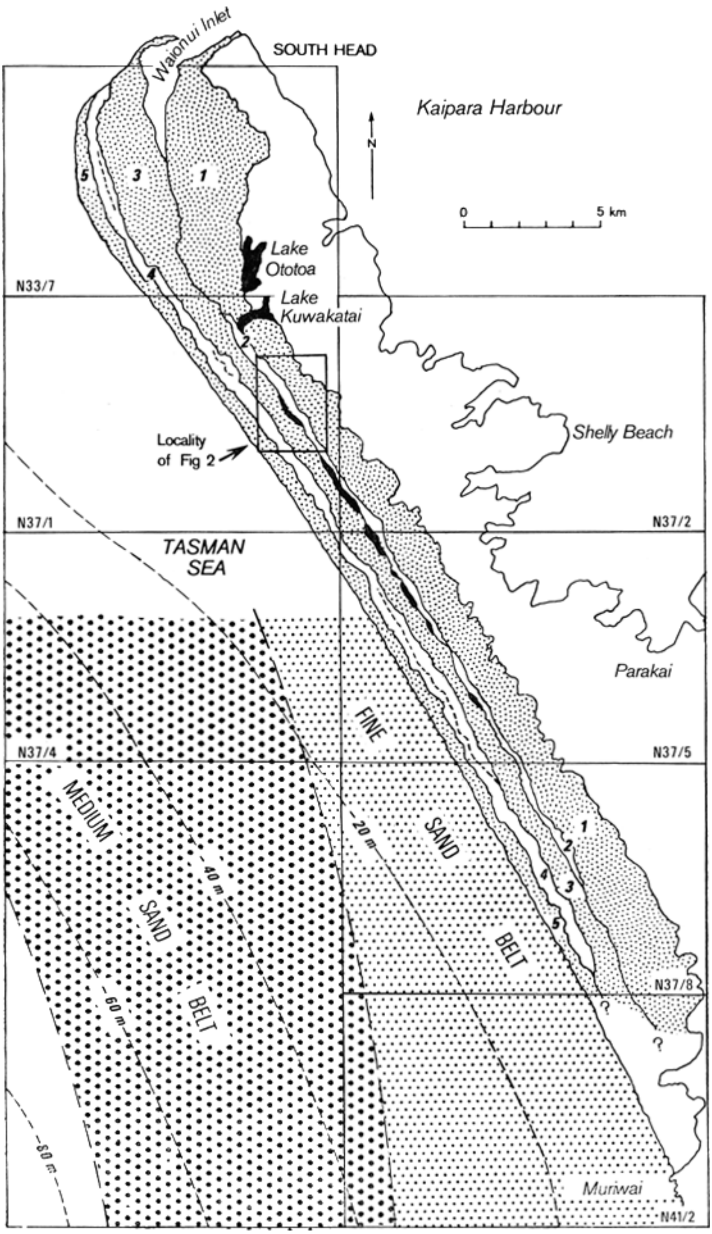
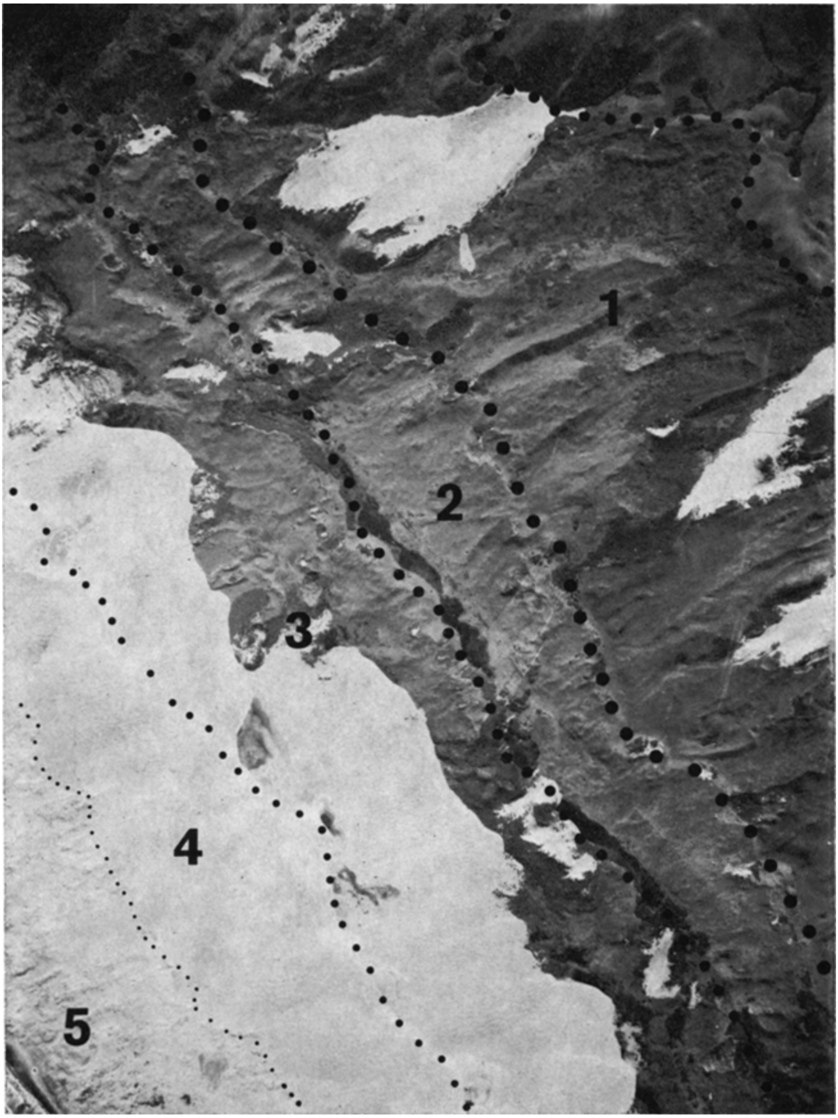


FIG. 1—South Kaipara Barrier. Post-glacial Dune Belts 1–5 are shown in alternate stipple and blank patterns. Dashed line divides Dune Belt 4 into two main phases. Off-shore sediments and submarine contours after McDougall & Brodie (1967). N33/7, etc. = sheet numbers from the NZMS 2 topographical map series. For locality see Fig. 6.



Dept. Lands & Survey photo

FIG. 2—Aerial photograph illustrating the five dune belts. Note parabolic form and vegetated nature of Dune Belts 1, 2, and 3; transverse dunes in Dune Belt 4 and their overlap on to Dune Belt 3; and the irregular nature of Dune Belt 5. For locality see Fig. 1. Published by permission of the Surveyor-General, Department of Lands and Survey.

TABLE 1—Volumes of sand (in $m^3 \times 10^6$) in Dune Belts 1–5, correlated with sea-level fluctuations

	Dune Belts				
	1	2	3	4	5
VOLUME OF SAND					
N33/7*	500·0	0	155·0	63·8	23·0
N37/1–2*	638·5	216·5	328·5	176·5	79·6
N37/5*	716·5	104·5	237·0	152·0	51·9
N37/8–9*	667·0	97·0	251·0	126·0	61·0
TOTAL	2522·0	418·0	971·5	518·3	215·5
CORRELATION WITH SEA-LEVEL FLUCTUATIONS					
Net sea-level fall (m)	0·9	0·27	0·49	0·17	0·26
Time span (years)	1500	900	500	1200	320

*Sheet numbers from NZMS 2 topographical map series (see Fig. 1 for locations).

Age

The immature soil developed on the vegetated dune belts and its absence on the younger non-vegetated belts demonstrates their post-glacial age. No contact of one belt with another is exposed. Thin peats have been recorded at shallow depths in several of the dune belts by some of the many drillholes drilled by New Zealand Steel Ltd, but these bear no relation to contacts between the individual belts and are instead related to the modern ground water level, including modern lake levels, that rises inland from the coast. They are, thus, almost certainly younger than the dune belts in which they are found.

Sand Volumes

Fifty foot (15 m) contours from the Lands and Survey Department and a planimeter enabled volumes of sand above sea level to be calculated (Table 1). The total volume of post-glacial sands should be reasonably accurate, but the volumes for the individual dune belts may be less accurate because of continued inland movement of each belt before it was finally halted by vegetation. However, it is assumed that this movement has not greatly affected the width and height of each dune belt.

Dune Belt 1 was split into two for calculation: a strip in front of the cliff, which can still be traced by a steep rise on the face of the dune sand which buries it, and an area behind the cliff. The inland margin of the dune belt behind the cliff has a steep front that rises commonly 30 m above the buried landscape. As the latter is visible as windows within the dune belt an average of 15 m was assumed for the thickness of this portion of Dune Belt 1. The volume in front of the cliff was calculated as a wedge of sand using local averages of its height above sea level to estimate thickness.

Because Dune Belt 4 and the vegetated portion of Dune Belt 3 rise to about the same elevation above sea level, it has been assumed that the non-vegetated portions of Dune Belt 3 (i.e., those portions that could be a cover of sand derived from an early phase of Dune Belt 4) have not increased the height of Dune Belt 3 substantially. Nevertheless, the quantity of sand that has been calculated for Dune Belt 3 is possibly slightly too high; and that for Dune Belt 4 is possibly slightly too low.

SEA-LEVEL FLUCTUATIONS

The sea-level curve (Fig. 3) is modified from evidence obtained from the Firth of Thames (Schofield 1960) by correcting the ages given for ridges M12 and W2; the published ages for these ridges were inadvertently exchanged (see Schofield 1964), i.e., the age for W2 should have been given to M12, and vice versa. The age for the +1 m sea level (M11) is that obtained from an equivalent ridge at Matauri Bay which represents the same sea level (Schofield 1973). From its relative position and level, M2 is assumed to be of the same age as a −0·6 m sea level recorded by Schofield (1968). The ages have also been corrected for secular effects (Damon *et al.* 1972).

Coastal Effects

A rise in sea level promotes coastal erosion (Bruun 1962; Schwartz 1965). More recently it has been shown that the converse is also true—sea-level fall promotes both large scale progradation when it falls a metre or two (Schofield 1967a) and probably small scale progradation when the fall is only a few tens of millimetres (Schofield 1975). Each of the past sea-level fluctuations consisted of a fall in sea level which would have promoted progradation and a subsequent rise which would have promoted coastal erosion. Erosion not only provided the break in dune deposition to produce the distinct dune belts in the South Kaipara Barrier but could also have destroyed a portion of the previously prograded shoreline.

CORRELATION

Periodicity

An immature soil cover indicates that the dune belts are all of post-glacial age. Their individual ages are not known but as a first approximation Dune Belt 5 (i.e., the latest formed dune belt) is correlated with the last sea-level fluctuation, which dates from M3 to the present (Fig. 3), a period of approximately 320 years (the maximum regression to −0·6 m may have been about 240 years ago; cf. Schofield 1968, corrected after Damon *et al.* 1972). The preceding dune belts are correlated in turn with the preceding sea-level fluctuations (Fig. 3). Thus Dune Belt 4 is correlated with the fluctuations between M9 and M3, a period of about 1200 years; during

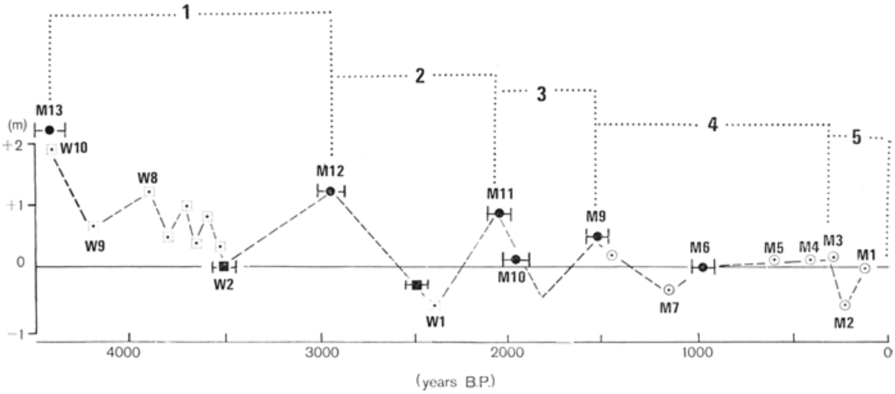


FIG. 3—Sea-level fluctuations after Schofield (1960; 1964; 1968; 1973) correlated with Dune Belts 1–5. Squares (and numbers prefixed by W) denote control points from the Whakatiwai beach traverse; circles (and numbers prefixed by M) denote control points from the Miranda beach traverse; solid symbols indicate points dated by radiocarbon analyses—the range for each date is denoted by the lateral extensions (see Schofield 1960, fig. 8).

this period as in Europe (see Schofield 1960, fig. 8), two periods of transgression are suggested by the physiography of the belt. Dune Belts 3 and 2 are correlated with the fluctuations between M11 and M9 (500 years) and M12 and M11 (900 years), respectively. Dune Belt 1 is correlated with the fluctuation from M13 to M12 (1500 years); this fluctuation includes a number of minor fluctuations which probably had no noticeable additional coastal effect since none were higher than M12.

Progradation and Sea-Level Fall

In correlating a sea-level fluctuation with coastal progradation (Fig. 3) it is not the maximum fall of sea level during a fluctuation that is important but the net fall between sea-level maxima. For example, it is not the fall between M12 and W1 that is important but the net fall beween M12 and M11 (Fig. 3).

As sea level falls the sea floor is kept in equilibrium with sea level by the removal of a layer of sediment. Some of this sediment is thrown ashore but some is probably moved to deeper regions beyond the local maximum depth of sea-floor equilibrium. The rate at which the profile of equilibrium is re-established would probably be much faster near shore where the rate of erosion would be greatest. Thus initially, at least, the layer of sediment removed from the sea floor is likely to be wedge-shaped, thinning away from the shore. There must also be a lag between cause and effect; the faster the rate of sea-level fall and the wider the sea-floor profile of equilibrium, the greater this lag is likely to be (see Bruun 1962 and Schwartz 1968). However, if equilibrium of the sea floor were attained

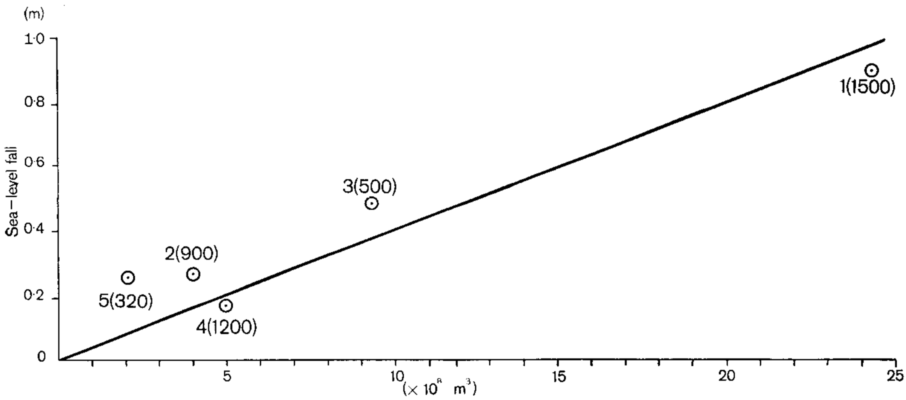


FIG. 4—Sea-level fall plotted against volume of sand for Dune Belts 1–5. Numbers in brackets refer to length of period in years for each sea-level fall. The line showing an approximate linear relationship commences at the zero points for both parameters on the assumption that very little sand is derived from other than the sea floor (see text).

during each sea-level fluctuation the amount of coastal progradation should be proportional to the net sea-fall. For the South Kaipara Barrier Fig. 4 shows there is only a rough proportionality, but it may be significant that those sea-level fluctuations which have the longest time to achieve possible equilibrium lie below the graph where it would appear that there is "too much" progradation, whereas those with shorter times lie above the graph where there would appear to be "too little" progradation. Thus time would appear to be important; this relation is emphasised by plotting the time span for each sea-level fluctuation against the associated "deficit" or "excess" in progradation (Fig. 5), when it is found that there is a poor but definite relationship.

SAND ORIGIN

Egmont-Kaipara Sand System

The source of most of the sand for the South Kaipara Barrier, and for the post-glacial dunes along its west coast in particular, is considered to be from off-shore and hinterland areas between Mt Egmont and the Kaipara Harbour (Fig. 6). From a quantitative, sand-movement point of view (see below) this region is considered to be a single entity, here called the **Egmont–Kaipara Sand System**.

South of Mt Egmont the D'Urville Current sweeps south-eastwards (Brodie 1960) and has no doubt influenced the net longshore drift towards Wanganui (Burgess 1971). North of Mt Egmont the Westland Current (Brodie 1960) sweeps northward and not only influences the net northward, near-shore drift of the Egmont Blacksand Facies (Schofield 1970)

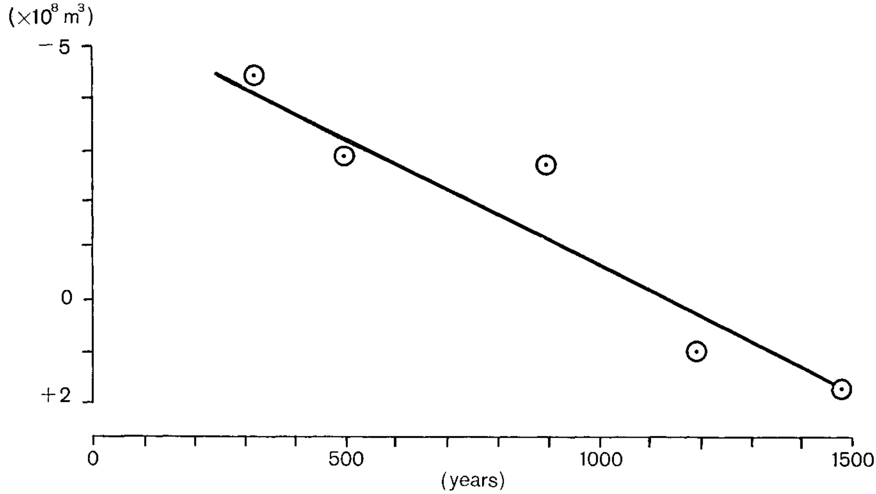


FIG. 5—"Deficient" or "excess" volume of sand for Dune Belts 1–5 (from the graph in Fig. 4) plotted against time span for the associated period of progradation.

but has almost certainly caused an off-shore northward drift of sand as well. The effect of this current extends north to the mouth of the Kaipara Harbour where it meets the West Auckland Current (Brodie 1960), which sweeps south-eastwards and has caused the longshore drift in this direction (Schofield 1970). The meeting place of these two currents has no doubt shifted up and down the coast, allowing the mixing and widespread development of the West Auckland Sand Facies (Schofield 1970). However, it is effectively opposite the Kaipara Harbour entrance, as is shown by the positions of the large and ancient North and South Kaipara Barriers, which have grown south-eastwards and north-westwards, respectively.

History

Comparison of the modern coastline with its position plotted on 115–120-year-old Admiralty Charts suggest that there has been little change along the coasts of the South Kaipara and Manukau Barriers during the last century. The only difference is at the northern end of the South Kaipara Barrier where there seems little doubt that the 1858 Chart is inaccurate. According to it, the ocean coast near the north end of the barrier lay to the east of Dune Belts 4 and 5. This seems highly unlikely.

Discussions with Maoris (Smith 1878) led to the following unsolicited information. "Many generations" prior to 1865, old tribal boundaries had extended seaward of the present coast between the northern and southern ends of the Manukau Barrier. This land consisted of "low, sandy country, with numerous sand-dunes, fresh-water lakes, with clumps of tall manuka

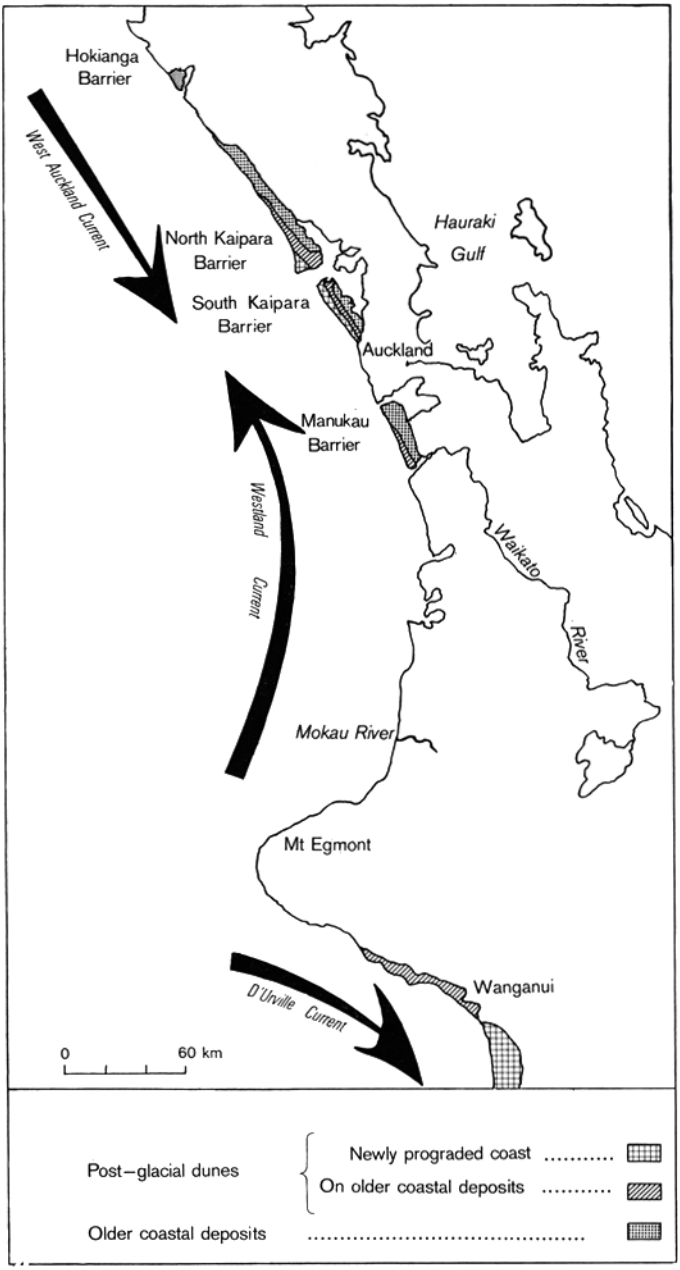


FIG. 6—Post-glacial progradation, west coast, North Island. The Egmont–Kaipara Sand System extends from Mt Egmont to Kaipara Harbour. Major currents after Brodie (1960).

trees scattered over its surface. The lakes were much resorted to by the natives . . . on account of the great numbers of eels found in them." In fact, it was land similar to the prograded portion of the South Kaipara Barrier that is still preserved seaward of the old cliff line. By 1878 the ocean coast of the Manakau Barrier was "an almost continuous line of steep cliffs, with, at their base, in some few places, a small strip of sandy flats generally covered with manuka; but even these are fast disappearing, as I learn from a settler resident in that locality." These flats have since completely disappeared. As pointed out by Smith, the almost continous belt of post-glacial dunes on top of the high cliffs along the ocean coast of the Manukau Barrier is further evidence of a previously prograded strip in front of the cliffs, i.e., of dunes heaped up against the cliff enabling sand to travel up to its present level (compare the same situation still preserved along the South Kaipara Barrier).

Smith also records that within the personal memory of his informant, Aihepene Raihau, dry land existed on parts of the present Manukau bar. "The natives did not, as I understood him, live upon these banks, but used to make periodical visits to them in their canoes, for a few days at a time for fishing purposes, living in houses which they had constructed there." The natives of Kaipara also have a tradition (Smith 1878) "that the banks of the bar of that harbour were once dry land upon which their forefathers lived and cultivated; but this must have been at a much earlier age . . . for here we find that this tradition is mixed up with one of their old myths."

Beaglehole (1968) states that in January 1770 Cook sailed in close (to within 3 or 4 "leagues") to investigate a possible inlet on the same latitude as the present Kaipara Harbour entrance but "found that it was neither a bay or inlet but low land bounded on each side by higher lands." Was the bar an island at this time?

This information is consistent with a period of greater coastal progradation at some time prior to 1865, its maximum being "many generations" before. As a Maori generation of that period is generally considered to have been 20 to 25 years, this description fits with a sea level low of about 1700 to 1750 A.D. (Fig. 3). Then the latest period of progradation would have been at its maximum, since when, as a result of sea-level rise, there has been much erosion. Continued longshore drift, including material derived by erosion of the Manukau Barrier, has preserved more of the prograded South Kaipara Barrier.

Hinterland Source of Sand

The catchment region from which newly-derived sand could enter the Egmont–Kaipara Sand System is divisible into two almost equal areas: the Waikato River catchment of 14 200 km^2, and the balance, including the headwaters of the Kaipara Harbour, of about 12 500 km^2.

Waikato Catchment

Most of the Waikato catchment is formed of easily eroded, rhyolite-derived sand. As a result, the riverbed is a carpet of sand that is ever shifting down stream even during low rates of flow. The median grain size of this material ranges from 0·27 to 0·5 mm near its mouth and is coarser up stream.

Man has interfered with the catchment in a number of ways and, thus, the present bed-load movement must be assessed in the light of these interferences. Comparison of silting surveys during the first third of this century with the amount of aggradation since the deposition of the Taupo Pumice Alluvium in 130 A.D. shows that a man-caused change in vegetation has speeded up, or has been the sole cause of, 10 m of aggradation in the Waikato River during the last 1000 years or so (Schofield 1967b). However, since the establishment of hydroelectric dams in the upper waters of the river and the dredging of large quantities of sand in its lower reaches, there is now a change to overall scour. Engineers of the Waikato Valley Authority have compared the net scour as determined from measured sections during the period 1964–70 with the total removal of sand by dredging and found that the scour was almost precisely 1·5 times the volume of dredged sand (G. T. Riddall, Engineer, Waikato Valley Authority, pers. comm.). The excess amount of scour is almost certainly due to silting within the hydroelectric dams. The action of scouring to replace man-removed sediment is no doubt assisted by the previous 10 m aggradation caused by man and the fact that scouring is happening suggests the present bed-load movement near the mouth of the river is probably close to normal.

The rate of sediment-yield depends on the water flow, and a significant portion of sediment is moved during flood time. A method to predict the sediment-yield is described by Simmons (1959), who recommends the use of a discharge equal to the "annual flood". (This discharge is divided into the run-off of the catchment to determine the number of days required to multiply the sediment-yield of the annual flood, so that the annual sediment-yield can be determined.) The annual flood for the Waikato River is approximately 850 m^3/s and bed-load movement in cubic metres per day at such times is 650 at "The Elbow" and 120 at the Waikato Heads (C. H. Elam, Engineer, Ministry of Works, pers. comm.). "The Elbow" lies up stream of "The Delta", which is an abnormally wide portion of the river full of sand islands (Fig. 7), and the reduction of load between "The Elbow" and the heads is thought to be a due to a temporary deposition at "The Delta". This area does not appear to be a permanent sedimentary trap; the downstream limits of the sand islands are the same on the 1851 Admiralty Chart as they are today. Therefore, the bed-load movement during the annual flood is taken as approximately 650 m^3 per day. This is equivalent to 42 000 m^3 per year as determined by the method described by Simmons (1959), with an average annual rainfall for the catchment of 1300 mm (N.Z. Soil Conservation and Rivers Control Council 1957).

Bed load is only part of the total sediment-yield. Unfortunately, there are no grain-size analyses or volumes for the amount of suspended load in the Waikato River but it is generally considered (e.g., Allen *et al.* 1972) that although the great bulk is less than 0·12 mm, suspended material can include sand up to 0·25 mm. Thus suspended load is important in considering the origin of dune sand that averages about 0·18 mm. Kukal (1971) quotes a range for suspended load in lowland rivers of "10 to 20 times the bed load" and this is perhaps much more in "large rivers". Because of

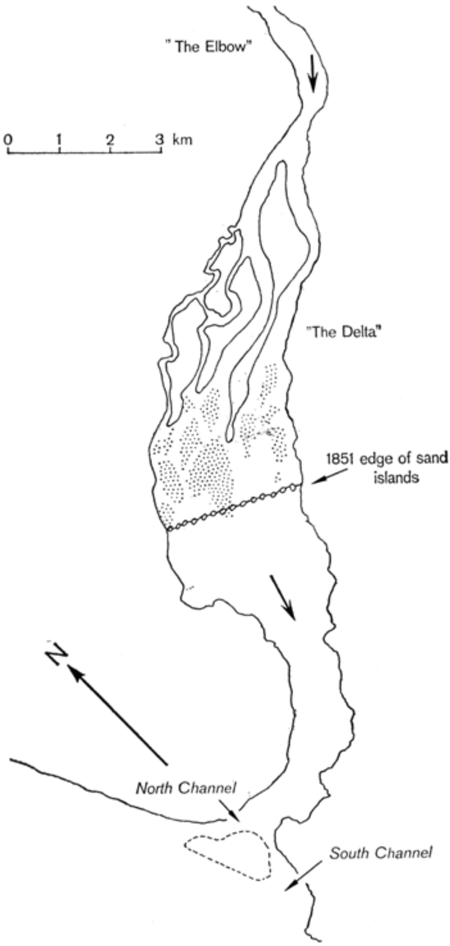


FIG. 7—The Waikato River near its mouth showing coincidence of the downstream limits of sand islands, today (stippled) and in 1851.

the nature of its headwaters and the unusual amount of sand being constantly transported, the amount of suspended load in the Waikato River is not thought to be much greater than its bed load. If any thing, Mr G. T. Ridall of the Waikato Valley Authority, considers that the ratio of 10 to 1 accepted for this paper is excessive. If 10% of the suspended load has a median of 0·18 mm then the amount of suspended sand that reaches the coast, and that could form part of the dune sands, equals the bed load.

Although the bed load is considerably coarser than 0·18 mm it must eventually break down to smaller particles and hence the total dune sand derived from the Waikato is thought to be about twice its bed load. At least one-third of this is lost to wear and tear as is shown by the reduction

TABLE 2—Mineralogy of off-shore samples compared with Kaipara Dunes and Waikato River

Sample Number*	Quartz (%)	Soda-calc Feldspar (%)	Potash feldspar (%)	Mafics† (%)	Residue (%)
A (C301)	48	37	5	8	2
B (C300)	48	40	1	9	2
C (C299)	52	37	1	10	1
D (C298)	56	26	7	4	6
E (C297)	54	34	0	8	4
F (C296)	49	37	2	10	2
G (C295)	43	30	6	11	10
H (C337)	47	30	4	15	3
I (C336)	44	44	2	9	2
J (C335)	53	34	3	9	2
K (C334)	39	32	6	19	4
Average off-shore‡	48	35	3·5	10	3·5
Kaipara Dunes§	51	29	4·3	12	3·2
Waikato River (Schofield 1970)	19	37	1·6	4	38·0

*Sample numbers A–K are shown in Fig. 8. N.Z. Oceanographic Institute sample numbers (from McDougall & Brodie 1967) are given in parentheses.
†Known percentages of magnetic mafics were removed before the samples were received; the mineralogical percentages have been corrected for this factor.
‡Average of samples A to K inclusive.
§Average of 12 beach and post-glacial dunes of the South Kaipara Barrier (from Schofield 1970; samples with abnormally high mafic content have been excluded).

in the rock fragment fraction (compare mineralogical analyses in Table 2). Thus the total volume of sand from the Waikato River that could assist in building in the post-glacial dunes of the Egmont-Kaipara Sand System is 42 000 m^3 (bed load) $\times$ 2 (factor for total load) $\times$ 0·67 (factor for breakdown of fragments) $\times$ 4425 (time in years during which dunes were built). This equals $2{\cdot}4 \times 10^8$ m^3 or about 4·7% of the total dune sand (total of $46{\cdot}4 \times 10^8$ m^3 as measured in the South Kaipara Barrier plus about 10% of that figure for the post-glacial sand dunes that are still preserved in the Manukau Barrier).

Catchment Balance

The balance of the catchment area is formed of rocks that are much more resistant than those within the Waikato River catchment and because it is also of a lesser area the amount of sand it must have contributed is probably considerably less than 4·7% of the total post-glacial dune sand, say about 2%.

Conclusion

The above discussion suggests that input of fresh sand into the Egmont–Kaipara Sand System has supplied only about 6–7% of the total sand required to build post-glacial sand dunes over the last 4425 years. This estimate is obviously only an approximate one but is, nevertheless, of the right order.

Sand Scource from the Off-Shore Sand Belt

Grain Size

The off-shore sediments within the Egmont–Kaipara Sand System are described by McDougall & Brodie (1967). Their samples were collected along east–west lines; the lines were at approximately 40 km intervals. In Fig. 8 their grain-size analyses, reinterpreted in terms of median diameters in mm, are shown for the northern half of the Egmont–Kaipara Sand System. The isomedians for median diameters of 0·16 mm mark the eastern and western margins of an off-shore belt of coarser sand in which the median grain sizes almost invaribly have a restricted range of 0·16 to 0·19 mm. This "coarse" sand belt is separated from the shore by a finer sand belt in which there is a relatively very rapid decrease in grain size shorewards. Except off the South Kaipara Barrier and opposite the Waikato River mouth, the boundary between these two zones is at a fairly constant depth of between 49 and 53 m. The eastern bulge in this boundary opposite the Waikato River is probably caused by the relatively large amounts of coarse sand carried by that river. Its shallower position off the South Kaipara Barrier parallels a similar shallowing in the western 0·16 mm isomedian and is discussed below.

Mineralogy

McDougall & Brodie's (1967) sample lines are not close enough to construct meaningful feldspar–quartz isoratios as was done for studying sand movement off the Mangatawhiri Spit along the Northland east coast (Schofield 1967a). Furthermore, because coastal sands of the West Auckland region (including those on the South Kaipara Barrier) show that the West Auckland Sand Facies is very widespread (Schofield 1970), a request for samples for mineralogical study was restricted to a selection along two widely spaced sample lines (Fig. 8). The results show little mineralogical variation (Table 2). They also show that the average off-shore sand is very close to the average mineralogy of the South Kaipara Dunes and that it is quite distinct from the Waikato River sand. Although the Waikato River has probably supplied the bulk of the sand in the Egmont–Kaipara Sand System this mineralogical difference is to be expected. Wear and tear destroy the softer rock fragments—compare the differences between Hauraki (A) and Hauraki (B) Sand Facies (Schofield 1970)—and also the sand entering from the rest of the catchment is almost certainly much higher in quartz than that entering from the Waikato area.

Off-Shore Sand Movement

Tidal measurements at Auckland show that sea level has been rising at an increasing rate during this century (Schofield 1967a) and hence the near-shore, relatively fine sand is probably being temporarily deposited down to depths of 50 m to re-establish an equilibrium between sea floor and sea level. A cross-section through this temporary deposit is almost certainly wedge shaped, i.e., thickest near shore and thinning out at the depth of 50 m, beyond which there has been no further deposition. When sea level falls this fine sand will most likely be reworked and some of the fines will be carried beyond the western limit of the off-shore coarse and

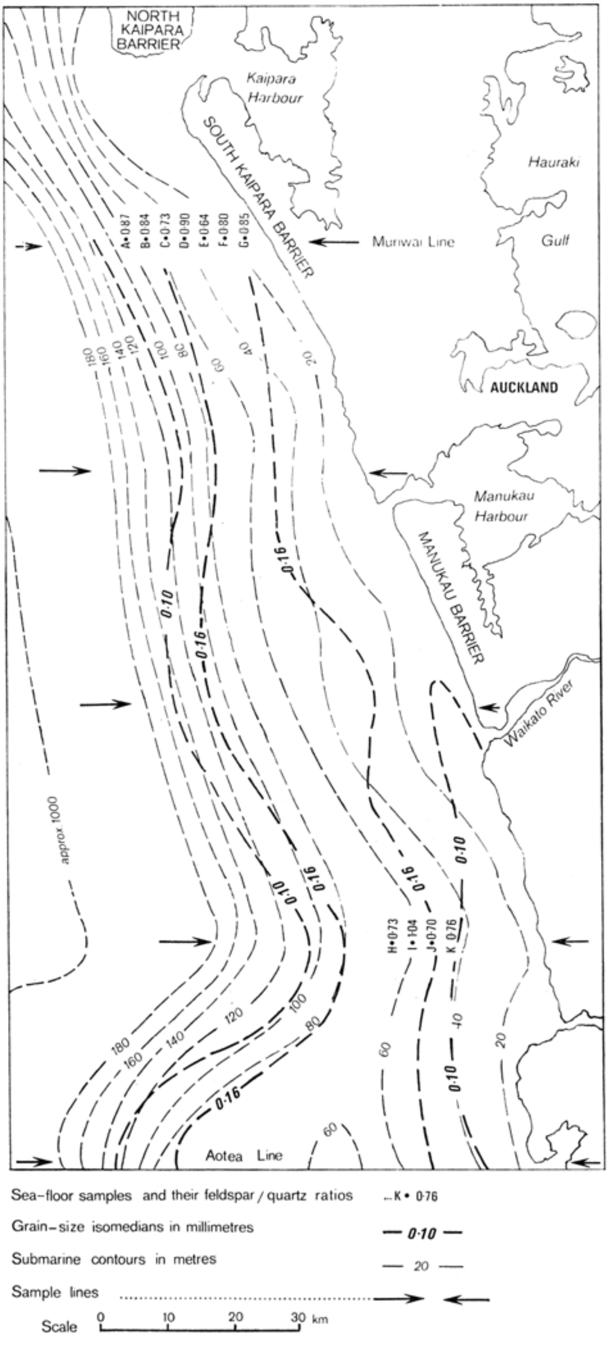


FIG. 8—Details for northern half of the Egmont–Kaipara Sand System. After McDougall & Brodie (1967).

zone, i.e., beyond depths of about 80 to 120 m. At the same time, longshore drift would carry the coarser fraction northward where it would become part of the post-glacial dune system. It is assumed that this has been the pattern during each of the post-glacial sea-level fluctuations. Therefore, as a first approximation, it is considered that the near-shore zone of the Egmont–Kaipara Sand System, down to a depth of 50 m (the limits of the present near-shore fine sand zone), is the area from which the greater part of the South Kaipara Barrier post-glacial dunes have derived their sand. This is an area of $60{\cdot}8 \times 10^8$ m^2. Because sea level fell by 2·1 m during the building of the post-glacial dunes, a wedge of sand measuring 2·1 m thick at its shoreward edge and approximately nil at a depth of 50 m, is likely to have been removed from this area. This totals $63{\cdot}5 \times 10^8$ m^3 of sand, which is close to $51{\cdot}1 \times 10^8$ m^3, the amount of sand in the post-glacial dunes ($46{\cdot}45 \times 10^8$ m^3 in the South Kaipara Barrier plus 10% for the amount of post-glacial dune sand remaining in the Manukau Barrier). The difference in these amounts could be due to a number of causes including the removal of the fine fraction to depths beyond the 80–120 m depth and some deposition on the sea floor in front of the prograding coast of the South Kaipara Barrier.

The near coincidence of these two figures, together with the almost identical nature of the mineralogy between the dune sand and the off-shore sand, and the impossibility of sufficient new sand being transported from the land to supply the volume of sand required during the period when the dunes were formed, shows that: (a) there has been substantial movement of sand on to the coast from the sea floor down to depths of at least 50 m; (b) the fine sand fraction has probably been transported beyond the 80 to 120 m depth; and (c) longshore movement has occurred over a distance of about 280 km.

This longshore movement of sand is considered to be due to the Westland Current, the effect of which is finally neutralised by the opposing West Auckland Current. The meeting of these two currents probably migrates up and down the coast but is most often opposite the mouth of the Kaipara Harbour. Their neutralisation is shown by the shallowing of the western margin of the off-shore coarse sand belt from between 80 and 120 m to 60 m off the Kaipara Harbour entrance, and the equal shallowing of the present day deposition of the near-shore fine sand belt (see above).

DISCUSSION

Sea-Floor Profile of Equilibrium

Figure 9A illustrates the differences between the sea-floor profiles near the northern end of the Egmont–Kaipara Sand System (Muriwai Line) and its central region (Aotea Line; see Fig. 8), and emphasises the shallowing of the sand belt at its northern end.

A number of questions arise. Are these two different sea-floor profiles, down to the outer edges of the sand belt, in equilibrium with present sea level, local currents, and energy input? Is the profile of equilibrium different

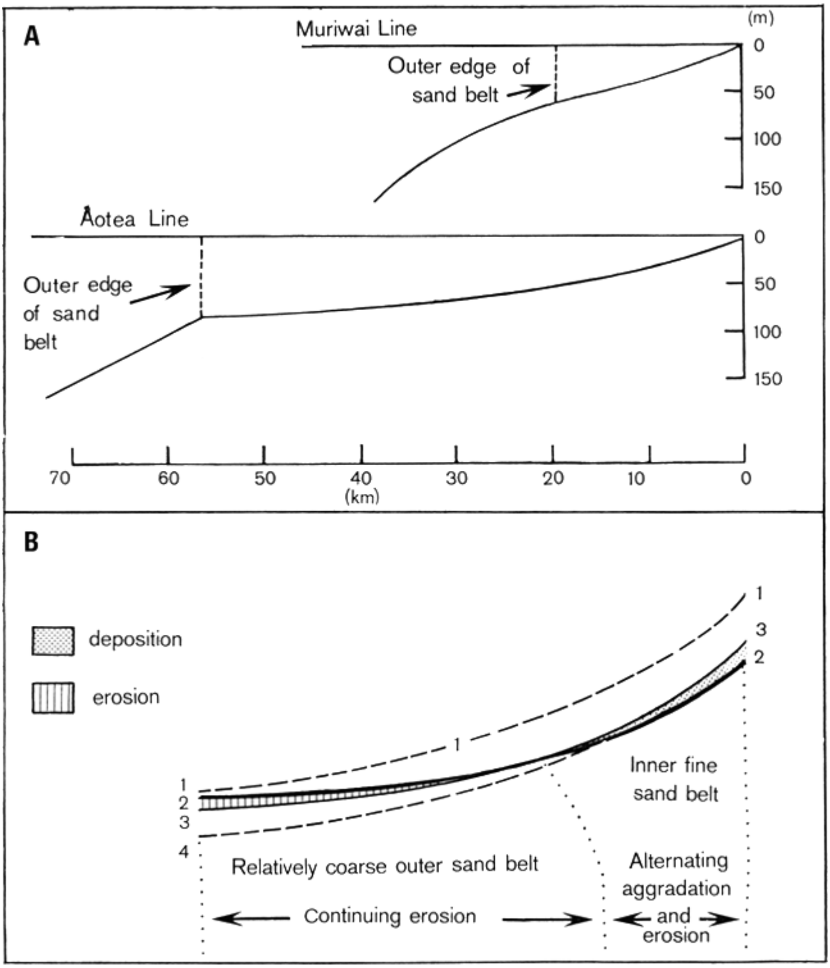


FIG. 9—(A) Sea-floor profiles along the Muriwai and Aotea Lines, northern and central positions, respectively, of the Egmont–Kaipara Sand System (for position of these lines see Fig. 8). After McDougall & Brodie (1967). The sea-floor profiles of partial equilibrium are thought to extend to the outer edge of the sand belt. (B) Hypothetical diagram illustrating past history of the local sea floor. Profiles 1 and 4 are in complete equilibrium at two different positions of sea level. Profiles 2 and 3 are in partial equilibrium. For further discussion see text. Profile 3 represents present conditions, except the amount of erosion shown, since Profile 2, is highly magnified and is probably negligible compared with the amount of near-shore deposition. The offshore coarser sand belt is almost certainly a lag deposit.

during periods of sea-floor aggradation compared with periods of sea-floor erosion? Or, in other words, is the layer of sediment that is removed, as sea level falls, of uniform thickness or is it wedge shaped, thinning with increased depth? If 4425 years is sufficient time for equilibrium to be established as a result of a 2·1 m fall in sea level, then the above evidence suggests that the layer removed was wedge shaped, that it extended down to a depth of only 50 m, and that it did not reach the outer edge of the sand belt. However, it cannot be certain that 4425 years has been sufficient time. Perhaps true equilibrium may only be reached by removal of a uniform, 2·1-m-thick layer down to the outer edge of the sand belt, i.e., down to depths commonly between 80 and 120 m. McDougall & Brodie (1967) considered that the coarser, outer portion of this sand belt could be a relict sediment "from earlier sedimentary environments" but conceded that there may be currents keeping it clear of mud and fine sand down to depths of 100 m. Their tentative suggestion that it may have been formed when sea level was 80 to 120 m lower is difficult to maintain because of the absence of fossil beach concentrates of black sand (McDougall 1961) like those common to the present beaches of the Egmont-Kaipara Sand System. On the other hand, the fact that finer material is not being deposited on the outer, relatively coarser portion of the sand belt is evidence that it is, in fact, part of the profile of equilibrium **which is not yet in complete equilibrium but which is still being eroded.** This is the opposite behaviour to the nearer shore portion of the profile where deposition is currently taking place as a result of sea-level rise. The partial neutralisation effect at the meeting of the Westland and West Auckland Currents (see above), causing the shallowing of the sea-floor profile of equilibrium (cf. Muriwai and Aotea Lines, Fig. 9A), is further evidence that the profile extends to the outer edge of the sand belt.

Figure 9B diagrammatically illustrates what could be taking place. Profile 1 (Fig. 9B) is the profile of equilibrium during a previous period of high sea level. Profile 2 is the result of a sea-level fall, whereas profile 3 is the result of a subsequent sea-level rise; neither profile 2 or 3 has reached equilibrium with its sea-level position. If sea level were to remain for sufficient time at position 3, the new profile of sea-floor equilibrium could be profile 4.

Relation of Depth of Sand Movement to Energy Input

Schofield (1975) provides evidence from three different energy environments on the east coast of Northland that shows that the sea-floor profile of equilibrium is a function of energy input and that there is a direct relationship between maximum depth of profile and magnitude of beach change. As no short-term beach changes have been surveyed within the Egmont–Kaipara Sand System it is not possible to relate their magnitude with the local off-shore profile of equilibrium. However, the Egmont–Kaipara Sand System is more exposed to the prevailing westerly winds than the east coast of Northland and must have a greater input of energy. Thus the maximum depth of the sea-floor profile of equilibrium and the depth down to which most sand movement takes place should also be greater. This is indeed the case. The area of greatest energy input on the east coast of Northland lies outside the Hauraki Gulf; here the profile of equilibrium extends to about 65 m and the greatest movement of sand occurs at about half that depth (see Schofield 1975). Within the Egmont–Kaipara Sand System the profile of equilibrium probably extends to the outer edge of the off-shore sand bank, that is down to depths between 80 and 120 m; the depth down to which the greatest movement of sand has probably taken place is 50 m (see above), i.e., again half the average maximum depth of the sea-floor profile of equilibrium. These conclusions are in keeping with the following observations. Ingle (1966) writes, "Recent observations by divers and from deep submersibles have emphasised the fact that sediment is in motion across the breadth of the shelf environment. The relative importance of sediment transport seaward of the breaker zone and mechanisms of transport have yet to be delineated. To date most authorities have *assumed* [my italics] that the foreshore–inshore zone constitutes the zone of greatest volumeric transport of sediment per unit of time." Similarly, Silvester & Mogridge (1970) consider that transport extends at least half way across the Continental Shelf.

CONCLUSIONS

(1) During the construction of the Holocene dunes in the South Kaipara Barrier, scources, other than the sea floor, could not have supplied more than a few percent of the sand volume required.

(2) Hence, it is not surprising that there are correlations between the mineralogy of the dune and sea-floor sand, and between progradational volumes and the net amounts of sea-level fall that occurred during several post-glacial sea-level fluctuations.

(3) Departures from proportionality in these latter correlations could be due to lack of time for equilibrium to take place between sea floor and the new, lower level of the sea. It is not certain that complete equilibrium has ever been reached—it probably has not.

(4) This dynamic, partial equilibrium between sea level and sea floor probably extends down to depths of 50 m or more off the west coast of Auckland and Taranaki. Complete equilibrium may involve sand movement down to depths of 80 to 120 m.

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