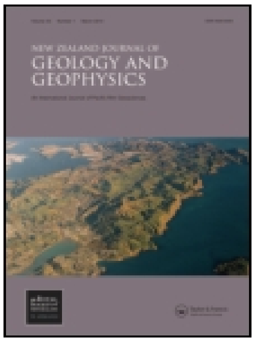

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SEDIMENT TRANSPORT ON THE CONTINENTAL SHELF, EAST OF OTAGO—A REINTERPRETATION OF SO-CALLED RELICT FEATURES

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ABSTRACT

The effects of offshore currents on the transportation of sediment to depths of over 100 m on the continental shelf, east of Otago, is illustrated by a description of the Southland Current and associated sea-floor sediments. Both erosional and depositional features which were formerly, but probably incorrectly, interpreted as drowned coastal land forms are regarded as examples of the present power of this current. A belt of fine sand between belts of nearshore and offshore coarser sediment does not necessarily mean that the offshore coarse belt is relict from some previous period of low sea level. Instead, the local offshore, coarse belt is almost certainly a lag deposit in partial equilibrium with today's currents, whereas the finer sediments between it and the shore are deposited where nearshore and offshore currents tend to nullify each other.

INTRODUCTION

Emery (1968) came to the conclusion that perhaps 70% of the world's continental shelves consist of relict sediments. However, he was careful to point out that "Greater or lesser reworking under present conditions in many areas probably has made new sedimentary structures with the old grains." (Included with these old grains must be fossil shells which need not necessarily date the associated structure.) More and more evidence is accruing that suggests both the mutually dependent "relatively-undisturbed-relict-sediment" and "no-transport-at-depth" hypotheses are largely, if not completely, erroneous (Hadley 1964; Ingle 1966; Draper 1967; Silvester & Mogridge 1970; Swift *et al.* 1971; many papers in Swift *et al.* 1972; Stahl *et al.* 1974; Schofield 1975b). The continental shelf should not be thought of as a little-modified, drowned landscape, but as a seascape in equilibrium, or approaching equilibrium, with present sea level. It is from this viewpoint that the sedimentological data (Cullen 1967; Cullen & Gibb 1966; Andrews 1973) and hydrological information (Burling 1961; Jillett 1969; Heath 1972; 1973) for the continental shelf off the east coast of Otago and Southland are here partly reinterpreted.

SOUTHLAND CURRENT

The relationship of the Southland Current to the coast of the southern part of New Zealand and to other bodies of water is shown in Fig. 1. Off the Otago Peninsula "the core of the current is centred over the 100 m isobath, moving slightly inshore during summer and slightly offshore during

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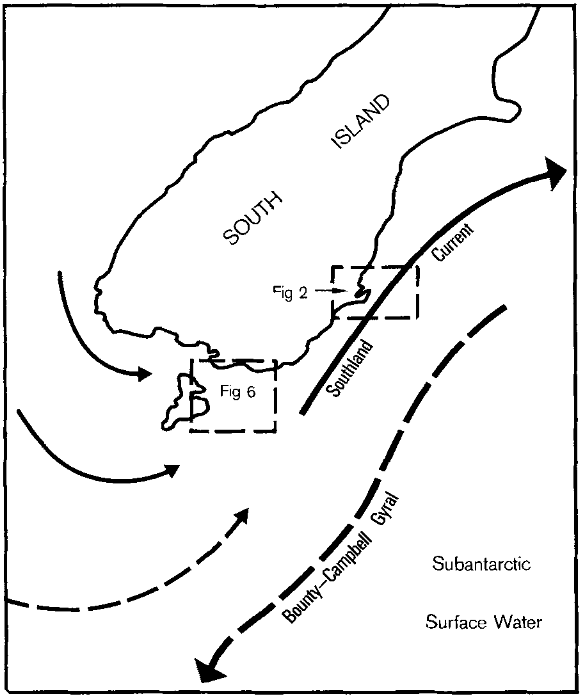

FIG. 1—Relation of Southland Current to land and Subantarctic Surface Water (after Burling 1961 and Jillett 1969). Localities for Figs 2 and 6 are shown.

winter. During midsummer the core lies at depths of approximately 38 m. It is possible that the core coincides with the zone of maximum current velocity. Preliminary measurements of current velocity and direction . . . in water depths of 100 m, show that both velocity and direction are highly variable at 85 m (e.g., 24–67 cm/s), and become more regular up through the water column. Sample readings include: at 65 m, 36 cm/s, the current flowing between north-west and north-north-west; at 35 m, 31 cm/s, the current flowing between north and north-north-east" (Andrews 1973, p. 797).

CONTINENTAL SHELF OFF OTAGO PENINSULA

Offshore Gravel Belt

A gravel belt lies off the Otago Peninsula (Fig. 2) between depths of mostly 40 to 100 m, and is separated from the shore by finer sediments. Its coarse-grained zone lies at 80 to 100 m. Because of the possible coincidence of the gravel belt with the "core" of the offshore Southland Current and the compatibility of the shells which commonly form 40–60% of the gravel with their present depth range, Andrews (1973, p. 825) concluded that the offshore gravel belt "must be considered in terms of modern hydrology."

However, his further conclusion that the coarse sediments "were supplied and redistributed by the [Southland] current during the early to middle phase of the post glacial rise in sea level" (p. 827) is not necessary (see below).

"Drowned Shorelines"

Despite the virtual absence of shallow-water species in the documented offshore malacology, Andrews believes there are several drowned shorelines off the Otago Peninsula. In general, his two best developed "shorelines" shallow northwards from −67 m to −56 m and from −104 to −88 m, respectively, at a constant rate of 1 m in 1300 m. This "tilt" must form part of the evidence for Andrews's Holocene folding, and acceptance of Andrews's suggested age for his −60 m "shoreline" implies that the rate of "tilt" is 0·0035°/1000 years. Although this is about one-quarter of the tilt rate known for the tectonically active Wellington and Wairarapa coasts (Wellman 1971a; 1971b; Lewis 1971; Singh 1971) it is at least eight times the expected local activity implied by Lensen & Suggate (1973). Because of this excessive tilt rate and the virtual absense of drowned shallow-water faunas, the interpretation that these morphological breaks in the sea-floor profile are tilted, but otherwise little modified, drowned shorelines is suspect, and other possible origins explaining their northward shallowing should be considered.

The Southland Current is confined by land and partly landlocked bodies of coastal water on its north-west margin and by a body of colder water on its seaward side (Subantarctic Surface Water at its surface and Antarctic Intermediate Water at depth—Jillett 1969). Although unlikely to be as effective as land, this body of cold water must assist in restricting the width of the Southland Current where it passes the out-jutting Otago Peninsula. Scouring of the sea floor would thus extend to deeper levels immediately off the Peninsula, and become less deep and less effective northwards. Thus the limited extent of the offshore gravel belt which disappears just north of the peninsula is explicable as a lag gravel without the need for northward transportation of pebbles. (See discussion on velocities required in section on *Polymodal Sediments,* below.) Though it is likely that there has been northward transport of sediment, there is no proof that this applies to the lag gravel—it is possible to derive all pebble lithologies from the neighbouring hinterland. Furthermore, the anomalous coarsest portions at its northern end (Fig. 2) suggest lag gravel rather than northward transport.

The −90 m "shoreline" lies close to the centre of the main gravel mode, whereas the −60 m "shoreline" lies at the centre of an incipiently developed subsidiary gravel mode (Fig. 2). Because the core of the Southland Current is thought to commonly lie above the centre of the main offshore gravel belt, the −90 m "shoreline" is almost certainly an erosive form cut by the current, and it shallows northwards as the current loses its velocity. Similarly, the −60 m "shoreline" is almost certainly formed by some current, either a secondary position of the Southland Current during its seasonal inland shift (Jillett 1969) or one generated by wave activity (cf. Fig. 3B). Because the −60 m "shoreline" also shallows northwards, the former cause is the more probable.

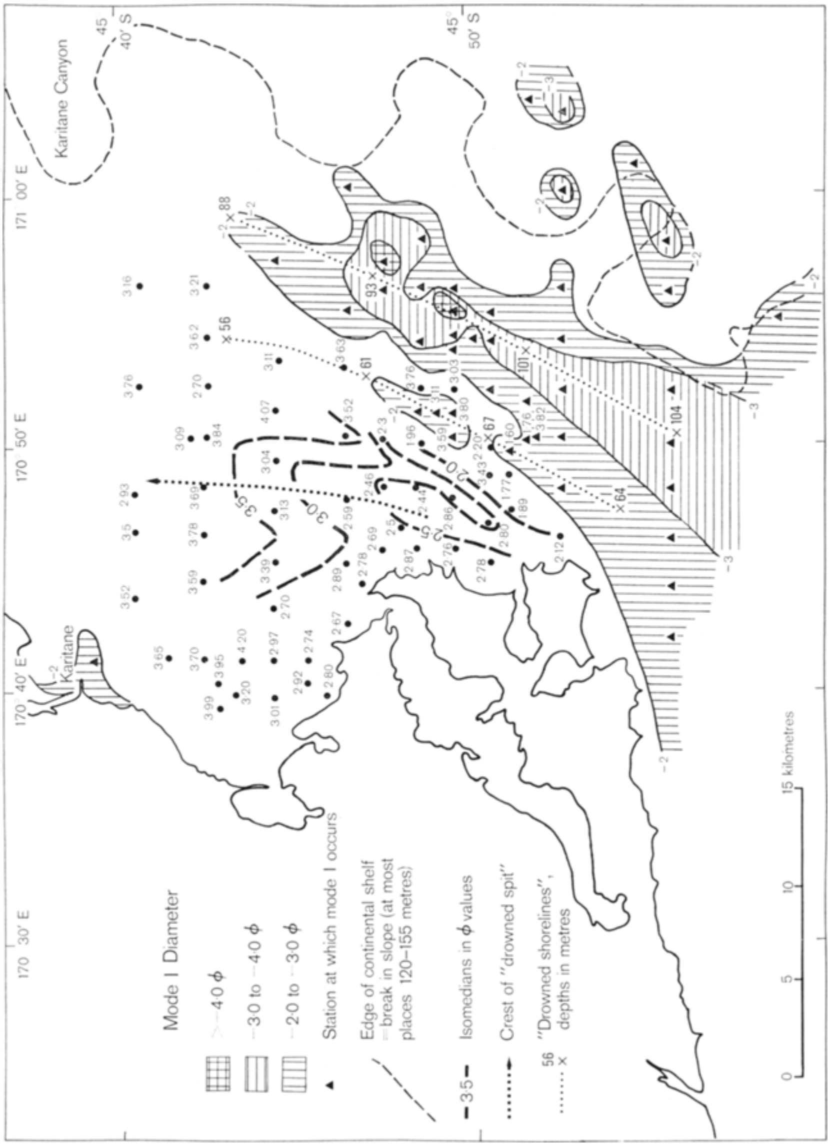

FIG. 2—Distribution of gravel mode off Otago Peninsula (after Andrews 1973, fig. 14) showing its relationship to so-called "drowned shorelines". Also shown is the median size (in phi values) of the detrital fraction of sediments associated with the underwater bar or "drowned spit".

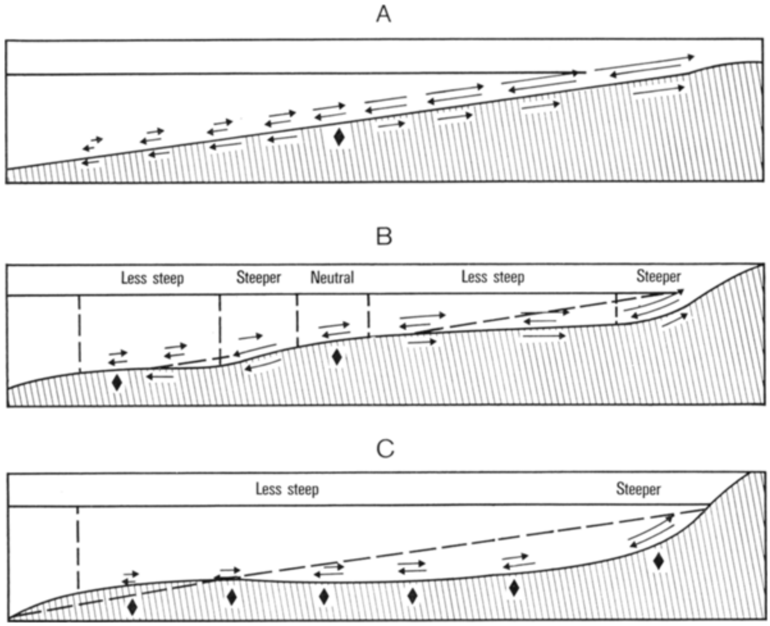

FIG. 3—Simplified and hypothetical, wave-base erosion on the sea floor (see Zenkovich 1967, pp. 106–11). (A) and (B) represent various stages in the development of a profile of equilibrium represented by (C). "The arrows of varying length above the surface of the bottom indicate the range of movement of the particles in both directions and the lower arrows indicate the resultant of these movements". The diamond-shaped symbol represents no net movement of sediment.

"Drowned Spit"

Just as Andrews believes that the "drowned shorelines . . . remain unburied by sediment" (p. 825), he presumably believes the "drowned spit" (Fig. 2) has remained almost unaltered—the regular decline along its crest is said to be "possibly a consequence of spit development during falling sea level" (p. 827). This regular decline in elevation northward is precisely at the same rate of 1 m per 1300 m as is recorded for the shallowing of the nearby "drowned shorelines"—the slope of the "spit" is, however, in the opposite direction. This is strong evidence that both the "drowned shorelines" and "drowned spit" owe their origin to one cause, namely, a decrease in velocity of the Southland Current after it passes the restriction caused by the Otago Peninsula. In the one case, erosion eases off in depth so that the "shorelines" shallow, and in the other case, deposition north of the Peninsula forms an underwater bar in which both quantity and grain size of the sediment decrease northwards. An underwater bar origin is discounted by Andrews because the sedimentary patterns of different modes appear to cut across it. However, the determination of sedimentary modes, by the methods used by Andrews, is difficult and uncertain and hence of doubtful value (see *Mode Determination* below). Furthermore, it is not known if one or more thin sedimentary layers were sampled, and because sampling was done over a period of several years (some in one year and nearby ones in another) **it is probably best to accept the median of all samples, irrespective of their polymodality, as representing average transport conditions.** The consequent relation of the "drowned spit" to the median grain sizes for the detrital fraction of its associated samples—unfortunately there are insufficient median grain sizes of the total sediment available—shows (Fig. 2) there is, in fact, a good parallelism of the sedimentary grain size distribution with the "drowned spit".

Furthermore, unless longshore drift had been at a very high rate it is extremely unlikely that a sandspit would have been preserved during the Holocene transgression, because a rising sea level promotes coastal erosion (Bruun 1962; Schwartz 1965; Schofield 1967, 1975a). For example the average volume change during 1965–68 was about 153 000 m^3 per year for the ocean beach of the Mangatawhiri Spit (see Schofield 1975a). With a much more rapid rate of sea-level rise than that at present, this could become the average coastal erosion rate during the Holocene transgression and it would take a little over a century to remove the spit completely. Has longshore drift been sufficient to counteract similar rates of erosion in the Otago regions? It is unlikely that, in post-glacial times, the local hinterland supplied more than a few percent of the sediment that forms any local prograded area. (Compare the contribution of less than 5% made by the Waikato River to the associated prograded coast, Schofield 1975b.) The great bulk was derived instead from the sea floor, as a result of sea-level fall. Sea-level change and sea-floor equilibrium are the great arbiters so far as coastal progradation is concerned. What the sea floor gives during sea-level fall is taken away during sea-level rise. The chances are that no permanent supratidal spit existed during the Flandrian Transgression. Furthermore, if new-material supply from the hinterland had been sufficient to counteract high rates of erosion, it should surely have been sufficient to have buried the so-called relict beach gravels and other relict modes described by Andrews (see section on *Polymodal Sediments* below).

It is quite possible that this underwater bar off the Otago Peninsula may have been the site of a sandspit at some time in the past, but to equate the modern feature with a "drowned spit" is unwarranted in the absence of more detailed information.

Polymodal Sediments

The offshore detrital sediments off the east coast of Otago are polymodal and Andrews (1973) recognises five modes. Mode I is the coarsest. He believes that by tracing the distribution of these modes "it is possible to determine the late Quaternary depositional history in the area".

Origin

There are a number of ways by which a polymodal sediment may be formed: (a) mixing of sediment from two or more sources; (b) influence of different lithologies at the same source (Andrews & van der Lingen 1969); (c) mixing of two or more thin layers during dredging of sample; (d) mixing of an old with a newly incoming sediment; and (e) generation of a new sediment within an old sediment by breakdown of some large particles. (Possibly (e) is required to account for the restriction of quartz "with yellow surface rind" to Andrews's sand Mode II. This, and his gravel Mode I, are the only two modes that have parallel grain-size distributions, which demonstrates their probable close relationship. Andrews concludes that the stained quartz in Mode II probably came from the highly quartzose coal measures of the Taratu Formation, but attempts no explanation of its absence in the other five modes. Could it be due to disintegration of ferruginous-cemented, quartzose pebbles from within the gravel Mode I? Such pebbles could have come from the Taratu Formation (see Harrington 1958). Cleansing action during longer periods of transport could explain the absence of ferruginous-stained quartz from the other modes.)

Andrews restricted the origin of the polymodal sediments to possibility (d), with each mode arriving at widely different times during the late Quaternary. He necessarily concluded that there has been a very slow rate of sedimentation, but more importantly implied that each mode has lain almost undisturbed since its deposition. This includes his Mode II (1·3 to 2·4 ϕ, medium to fine sand) which, according to his interpretation, was deposited during the early to middle phase of the post-glacial rise in sea level and prior to 8000–9000 years ago. The simplified Hjulstrom diagram (Fig. 4) shows that such a mode can be moved by a current moving about 20 cm/s which is considerably less than the maximum currents that are at present generated by the Southland Current (see above). Furthermore, the absence of epizoan growth from "most very fine pebble and granule size particles" (Andrews 1973, p. 801) as distinct from the epizoa-coated coarser pebbles, is further evidence that the Southland Current has been moving at greater velocities than 20 cm/s along the sea floor in the vicinity of Mode II in very recent times. However, the interstices of a lag gravel may afford some protection for fine-grained sediment, the latter being removed only under exceptional current velocities when it is exposed after movement of the gravel.

Mode Determination

Andrews's sediment analyses consisted of 0·25 ϕ fractions, but construction of polymodal sediments from sediments of known medians (Fig. 5) shows that Andrews's method of visual inspection does not produce accurate modal medians from polymodal grain size curves. This casts doubt on the grain-size distribution patterns for Andrews's modes.

Perhaps the only mode that can be considered a single entity is the lag gravel, Mode I. It is probably significant that it and its possibly dependent mode, Mode II, are the only modes that show a reasonably clear relationship with the Southland Current.

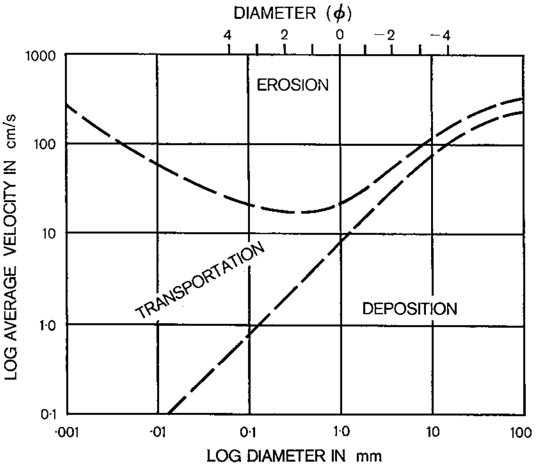

FIG. 4—Simplified Hjulstrom diagram (after Krumbein & Sloss 1951). Note increase in velocity required for erosion of particles finer or coarser than about 0·4 mm (1·5 φ).

CONTINENTAL SHELF OFF FOVEAUX STRAIT

The submarine sediment chart prepared by Cullen & Gibb (1966) shows that offshore gravels are confined to the Strait, and at deeper levels down to depths of 100 m south-east of Stewart Island and off the south-east corner of the South Island. They are generally absent to the south-east of Foveaux Strait between depths of 35 and 110 m. It is almost certain that these gravels are lag gravels that have a similar origin to the lag gravels off the Otago Peninsula (see above)—the effects of erosion of the Southland Current being less in the area immediately south-east of Foveaux Strait where it is less restricted. Furthermore, the underwater features of this particular portion of the sea floor which are described as "remnants of a pre-Flandrian shoreline along the eastern margin of the Strait, at a depth of approximately 35 fathoms" (64 m) (Cullen 1967) demonstrate the same relationship to the Southland Current as do the almost identical features off the Otago Peninsula.

The so-called −64 m shoreline consists of a sharp rise in the sea-floor profile at the north-west margin of a submarine plain that slopes south-eastwards. This break in the profile is not at a constant level. Isobaths (Cullen & Gibb 1966) show that it rises from about −82 m (45 fathoms, Fig. 6) immediately east of the north-east corner of Stewart Island, through −73 m (40 fathoms) off the centre of the eastern margin of the Strait to −64 m (35 fathoms) towards the northern part of the eastern margin of the Strait, and then back to −82 m off the south-east tip of the South Island (Fig. 6). It is clearly analogous to the shallowing of the −60 m "shoreline" off the Otago Peninsula and no doubt has the same origin. Furthermore, the fossil shells of early Holocene age that are thought to date this −64 m "shoreline" (Cullen 1970) are not directly connected with it and in fact occur at anomalous depths (Cullen 1970) when such a relationship is postulated.

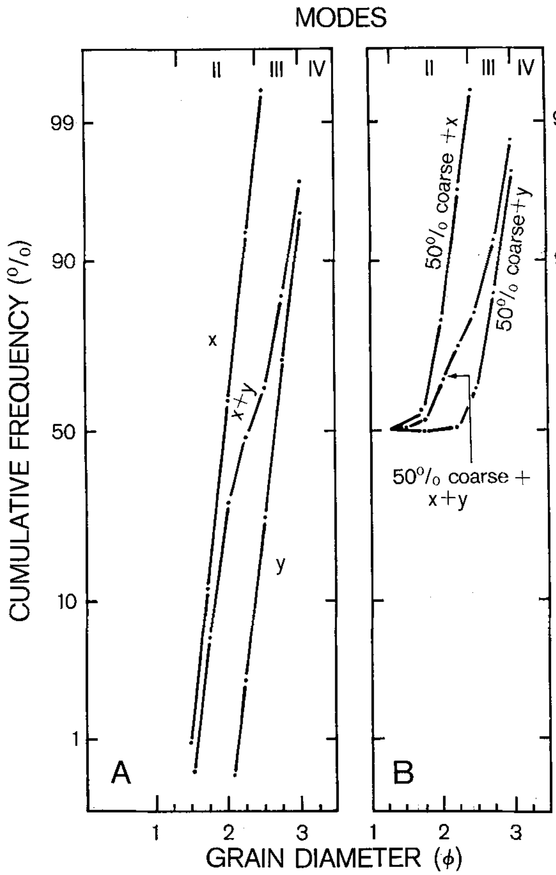

FIG. 5—All graphs constructed from 0·25 φ intervals. (A) Graphs x and y are two cumulative grain-size curves for sands with medians within Andrews's (1973) Modes II and III, respectively; x+y is a mixture of 50% x and 50% y. Note the bimodal curve this mixture produces. (B) The same cumulative grain-size curves as in (A), but added to a much coarser mode such as Andrews's gravel-pebble mode (not shown)—the latter is assumed to be 50% of the total sediment. *Note*: In (B) there could be uncertainty over whether x+y is the product of two sediments—compare this curve with Andrews's (1973, fig. 12) polymodal curves which contain more marked inflections in their trends. If polymodality is accepted, then by using Andrews's method of "finding (by inspection) the 0·1 φ interval between inflection points that contained the greatest amount of the mode" the calculated range of values for x and y medians are 1·75 to 1·85 and 2·5 to 2·6 φ, respectively, whereas their true medians are 1·95 and 2·66 φ. Similarly, the calculated medians for x and y from the x + y curve in (A) are again different, being 1·9 to 2·0 and 2·5 to 2·6 φ respectively.

Similarly, the "degraded longshore spit inundated by a recent rise in sea level" that is associated with the −64 m "shoreline" and which encloses the submarine Ruapuke Basin south of Ruapuke Island (Fig. 6)—interpreted as a "submerged coastal lagoon" (Cullen 1967)—is analogous to the submarine bar off the Otago Peninsula (see above).

NEARSHORE FINE BELT

One of the stumbling blocks in accepting the effects of offshore currents is the common presence of a nearer-shore belt of fine sediments. It has led instead to the commonly accepted belief of little sedimentary transport

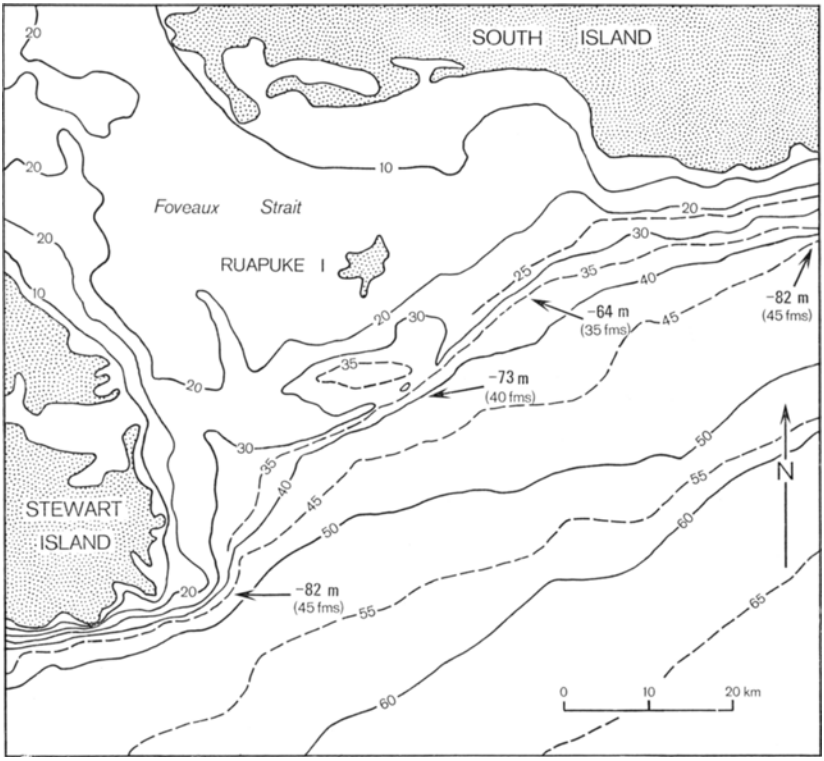

FIG. 6—Bathymetry of the Foveaux Strait area (after Cullen & Gibb 1966). Isobaths in fathoms. The different depths at which the sea-floor profile abruptly steepens are illustrated by depths in metres. Note relation of this margin to an underwater bar that forms the south-east edge of the submarine basin (Ruapuke Basin) south of Ruapuke Island.

beyond a depth of about 20 m, and the belief that any coarser sediment further offshore must be relict from some period of low sea level.

The inshore coarse sediment belt results from turbulence and currents generated by wind and tide. The offshore coarse sediment belt could in many areas result from an offshore current such as the Southland Current. Where this is the situation, the intermediate fine sediment zone must be the area where the inshore-generated currents meet with the offshore current and more often than not nullify each other to cause deposition of the fine sediment. During stormy periods (most often in winter) the strong inshore-generated currents would tend to force the offshore current seawards, such as occurs with the Southland Current (Jillett 1969). This concept also explains the nearer-inshore position of the offshore current outside Little Omaha Bay, and its part penetration onto land during progradation of the

Mangatawhiri Spit (Schofield 1967). This coastal penetration of the offshore current is shown by incoming of offshore, feldspar-enriched sand; by malacological studies; and by the support that both these lines of evidence gave to a single pattern of sedimentation during coastal progradation as distinct from a different pattern during coastal erosion (Schofield 1967, fig. 11). During this period of part penetration onto the coast there were still some inshore-generated currents, as must be expected, and hence the intermediate fine belt, although narrower, persisted.

CONCLUSIONS

(1) Offshore currents play an important role in transporting sediment along and across the continental shelf, and although their "banks" are mostly other bodies of water they behave in a similar way to other streams of water.

(2) The Southland Current is at present capable of sea-floor erosion and sediment transport down to depths of at least 100 m. This is demonstrated by the absence of shallow-water faunas directly connected with the so-called inundated shorelines off the Otago and Southland coasts; the relation of these breaks in the sea-floor profile to lag gravel, and their change in depth with the probable changes in the velocity of the Southland Current; and the relation of lag-gravel grain size to known velocity of the current.

(3) Because the Southland Current transports sediment it behaves in a similar fashion to longshore drift in that deposition of sediment forms underwater sand bars where current velocity is reduced. These have been formed at the contact of the current with partly land-locked bodies of coastal water.

(4) The frequent presence of a belt of fine sediment between nearshore and offshore coarser sediments does not mean that the latter is necessarily a little-disturbed relict sediment. Where the offshore coarse belt is related to an offshore current the intermediate fine belt is most likely the zone in which nearshore and offshore currents partly nullify each other. A careful study of current directions and velocities with depth above such an intermediate fine zone should disclose an extremely complex pattern.

(5) Despite the presence of an intermediate fine belt there must be times when there is a transfer of sediment across it from the offshore coarse belt onto the coast. This is shown by sedimentary and malacological patterns off Mangatawhiri Spit (Schofield 1967) and by quantitative studies in this area and of the Kaipara–Egmont Sand System (Schofield 1975b). In areas where sea level is rising in respect to the coast, this transfer may be masked at present by a net deposition of sediment on the sea floor.

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