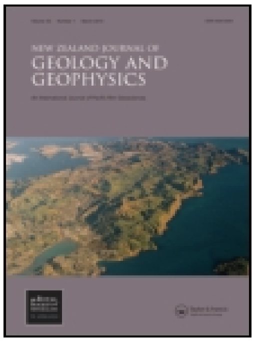

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ABSTRACT

The bathymetry, surficial sediments, and benthic assemblages of approximately 1190 km^2 of continental shelf and adjoining submarine canyons east of Otago Peninsula are investigated.

Pebble and sand fraction composition shows that the detrital sediments have been derived predominantly from the Otago Schists. The sediments are supplied to the continental shelf largely by the Clutha River 72 km south of the area, and are transported north by the combined action of the Southland Current and longshore drift induced by southerly swell.

The detrital sediments are polymodal, and by tracing the distribution of five prominent modes it is possible to determine the late Quaternary depositional history in the area. Sandy pebble gravel, which comprises a prominent and continuous band of gravel in mid-shelf position, extends from off the mouth of the Clutha to just north of Otago Peninsula, where it grades into sand. The distribution of sandy pebble gravel off the Clutha shows that it was supplied to the shelf during the early to middle phase of the post-glacial rise in sea level, and was distributed northward by the Southland Current. Probably as a consequence of a temporary halt in sea level rise 8–9000 years B.P., and of resulting aggradation of the lower reaches of the Clutha valley, supply of pebbles (Mode I) and medium sand (Mode II) ceased, and fine sand (Mode III) was furnished instead. Since sea level attained approximately its present position (*c.* 6000 years B.P.), only very fine sand and silt (Modes IV and V) has been supplied. Very fine sand and silt is accumulating over the inner shelf today, along with Mode III sand, which apparently is being reworked gradually northwards.

Holocene sand and muddy sand predominate over the inner shelf. Middle and outer shelf sediments consist largely of organic skeletal debris, except where pebble gravel occurs, indicating that negligible Holocene sediment reaches these areas. Middle and outer shelf sediment is therefore largely relict from earlier and lower sea level situations.

INTRODUCTION

The object of this investigation has been to chart and explain the distribution of surface sediments over the continental shelf adjoining Otago Peninsula. The area of study (Fig. 1) lies east of the peninsula, a Miocene volcanic complex, and extends from approximately the 10 m isobath to just beyond the edge of the continental shelf. The coastline is rocky and irregular, deep embayments being separated by promontories that terminate in cliffs 60–150 m high at their seaward end. The large embayments are tidal inlets protected from the open sea by bay-mouth bars and spits. Several small islands of Tertiary basalt occur just off the coast.

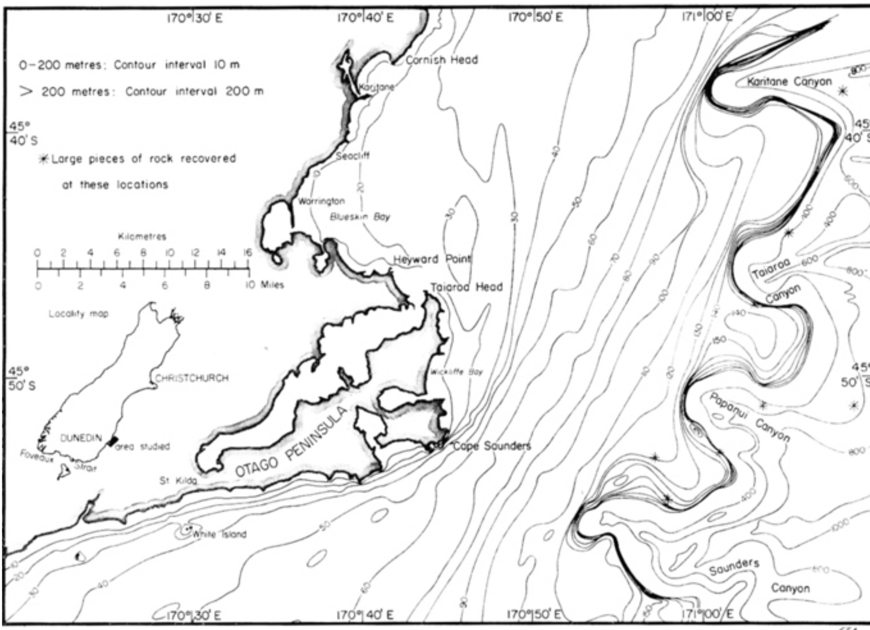

FIG. 1—Bathymetry; based on detailed soundings taken by HMNZS *Lachlan* in 1950. Locality map inset.

BATHYMETRY

Continental Shelf

The continental shelf slopes smoothly seaward, except where interrupted by drowned wave-cut cliffs, terraces, and a large spit (Fig. 1 and 2). Immediately off the south-east coast of the peninsula, where the shelf is only 11 km wide, the inner shelf slopes steeply at a gradient of 1 in 33 over a distance of 1–2·5 km (Fig. 2, profile D). Over a short distance the gradient decreases to average 1 in 170 out to the edge of the shelf. Further north, (about 1 km south of Taiaroa Head), the steeply sloping inner shelf levels out at 20 m to form a wide platform which is probably a cut surface veneered with sand (Fig. 2, profile C). Northward, the platform merges with a large submarine spit that extends for at least 13 km (Fig. 1; Fig. 2, profiles A and B). The crest of the spit lies at 20 m below sea level in the south, and slopes down northward to 25 m at profile A. The spit partly separates Blueskin Bay*, the shallow coastal embayment north of Otago Peninsula, from the open shelf. Blueskin Bay is deepest (30 m) immediately west of the spit. From the crest of the spit, the continental shelf slopes rather uniformly seaward at a gradient of 1 in 200.

*On nautical and hydrographic charts, e.g., N.Z. 66, the name "Blueskin Bay" is given to this coastal embayment. On topographic maps, e.g., NZMS 1, S164, the name is given to the large estuary and tidal flat west of the coast.

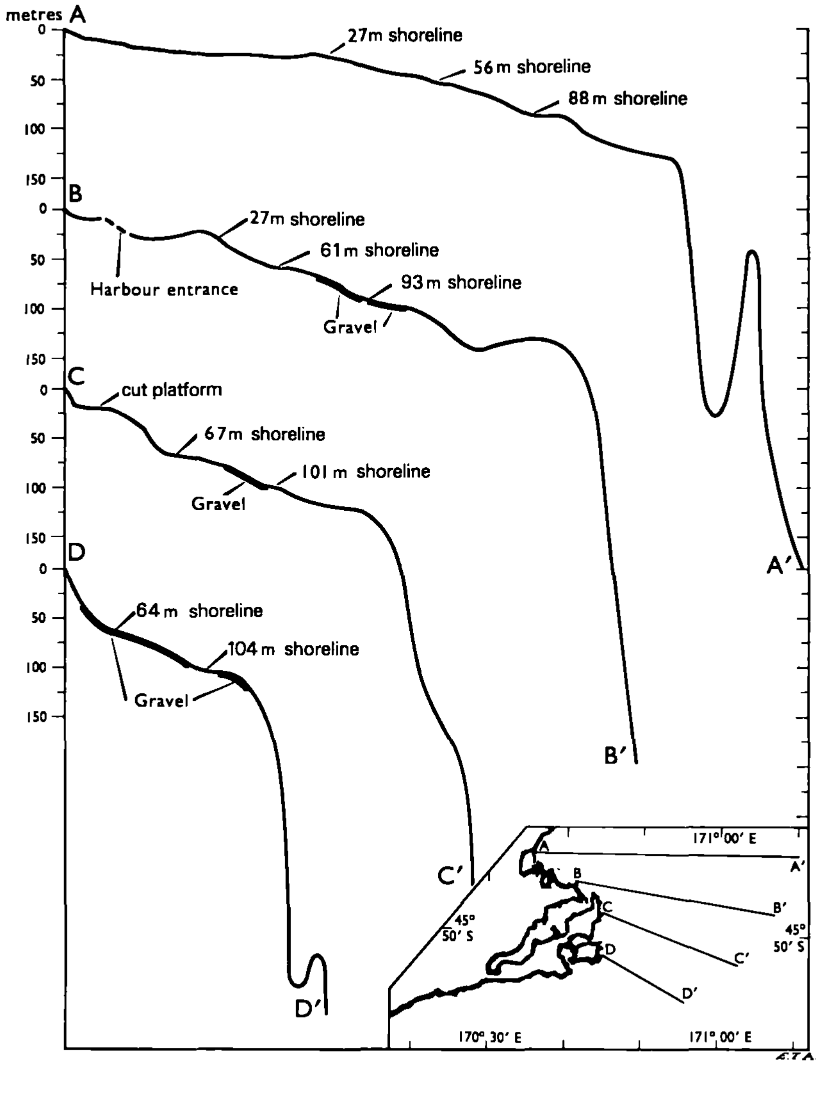

FIG. 2—Bathymetric profiles; constructed from soundings chart. Vertical exaggeration × 66.

Distinct breaks in continental shelf slope take the form either of a sharp step, or of a marked but smooth change in slope. Each break appears to mark the position of a shoreline formed during a Pleistocene low stand of sea level. One such shoreline, which occurs at 56–68 m in the study area, is continuously traceable as far south as profiles have been drawn (Kaitangata, South Otago), and probably coincides with Cullen's (1970) 64 m shoreline and lagoon in Foveaux Strait. Another occurs at 88–104 m, and though discontinuous, also can be traced to Kaitangata. A third and less persistent shoreline occurs at 113–132 m; it cannot be traced south of Taieri River mouth. Systematic changes in absolute elevation along each of the drowned shorelines suggest that growing folds cross the shelf obliquely at 3–4 places. The elevation changes are: 12–14 m for the 60 m shoreline, 18–27 m for the 90 m shoreline, and 15–21 m for the 120 m shoreline.

In the southernmost part of the area, small submerged spits, enclosed basins, and isolated banks occur at depths of 45–55 m. They form the northernmost occurrence of an extensive series of similar but larger features that are common south of the study area.

The break in slope that defines the edge of the continental shelf, occurs at 120–155 m at most places. The heads of submarine canyons commonly penetrate the shelf to the 120 m isobath, although Karitane Canyon penetrates to 72 m.

Continental Slope and Submarine Canyons

The continental slope is steep, gradients of 1 in 44 being typical, although gradients up to 1 in 8 have been measured around canyon heads. "Depth recorder" traces show that the slope is pinnacled at many places, especially around the heads of canyons such as Saunders and Papanui Canyons (Fig. 1). In addition, vertical faces, which are not revealed by the bathymetry, have been reported by the crew of the r.v. *Munida* (pers. comm.). Rock appears to be exposed at many places on the continental slope and on canyon walls, particularly where steep to vertical slopes are indicated, since large pieces of rock (up to 0·5 m long) have been recovered at 10 of 25 stations occupied in such areas. The recovered rocks are dominantly light grey to medium blue grey, brown-stained, massive, micaceous, locally calcareous, very fine sandy siltstone, silty very fine sandstone, siltstone, and mudstone. Many pieces are deeply bored, and several bear a thin (2 mm), almost black outer coating. Some pieces of siltstone are rich in pelecypods, and most pieces contain scattered thin-shelled planktonic and sparse benthonic foraminifera. No particular age is indicated, although a Late Tertiary age is most likely (P. N. Webb, N.Z. Geological Survey, pers. comm.). In addition to the fine-grained sedimentary rocks, scattered fragments of basalt and other fine to medium-grained volcanic rocks occur (Karitane Canyon), as do rare cobbles of metamorphic quartzite (Saunders Canyon).

As defined by the 183 m line, canyon heads tend to be rounded in plan view (Fig. 1). Nevertheless, the gross bathymetry shows the canyons to be crudely V-shaped valleys that combine eastward to merge with the Bounty Trough.

HYDROLOGY AND METEOROLOGY

Coastal Currents

Coastal water circulation in the area is dominated by the Southland Current (Brodie 1960), a confined surface current that flows north-east along the Southland and Otago coast. The Southland Current consists of subantarctic water mixed with Tasman Sea subtropical water that has been deflected south-east through Foveaux Strait and around Stewart Island (Burling 1961; Houtman 1966). Drift card and bottle observations (Brodie 1960) show that north-easterly flow of the current persists, although current velocity varies markedly throughout the year.

East of Otago Peninsula the Southland Current flows over the outer half, or more, of the continental shelf and over the upper continental slope (Jillett 1969). Its inner margin is always within 13 km of the shore (water depth approximately 70 m), and may extend right to the shore (as illustrated by Jillet 1969, fig 11, for January 1967). In the study area, Southland Current water occupies the complete water column over the shelf. The core of the current is centered over the 100 m isobath, moving slightly inshore during summer and slightly offshore during winter. During mid-summer 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, made with a T.S.E.2 meter at station Mu 69–66 (Fig. 3) 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-east; at 35 m, 31 cm/s, the current flowing between north and north-north-east. (Each figure is the average of five measurements.)

Tides and Tidal Currents

The local astronomical tide is diurnal. At the entrance to Otago Harbour, the mean tidal range varies between 1·7 m (springs) and 1·3 m (neaps), (New Zealand Tide Tables for the year 1967). Measurements at a station 9·5 km east of the harbour entrance and where water depths are approximately 36 m, show that the flooding tide sets initially to the west-north-west (at 10 cm/s), and progressively changes direction clockwise to flow north at high water (at 51 cm/s), and east-north-east just before low water (at 5 cm/s). At low water no measureable current exists (Hydrographic Chart N.Z. 66 for 1956).

Winds

North-east and south-west winds are equally prevalent (20–25% of the year according to data quoted by Elliott 1958), the latter being the strongest and the source of most gales, and hence the one most likely to influence sediment transport and erosion.

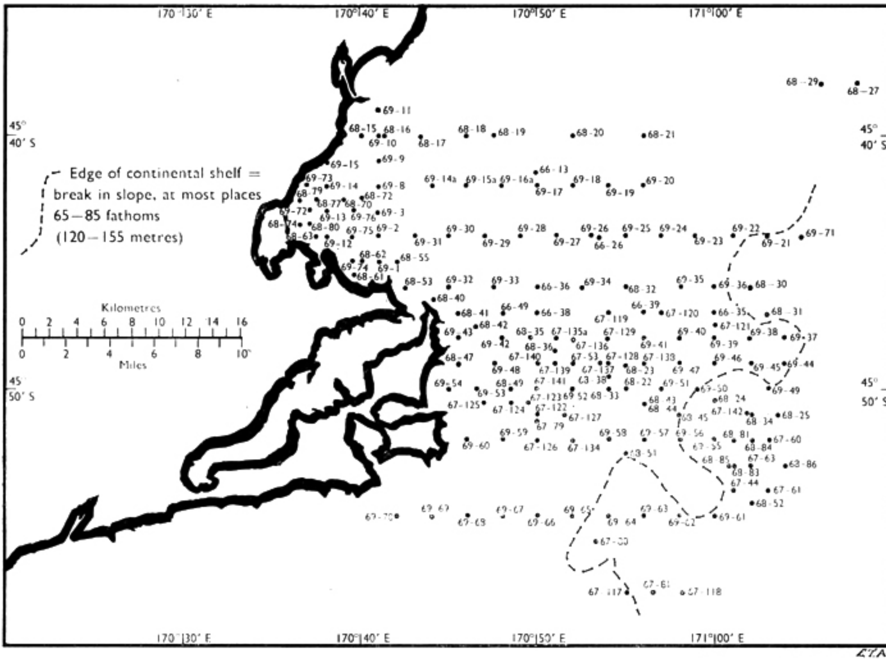

FIG. 3—Sampling stations collected by r.v. *Munida*. For each station the full identification is prefixed by Mu, e.g., Mu 67–117.

Waves

Wave conditions must influence the nature and direction of sediment transport over the inner shelf. They are unlikely to be significant over the outer two-thirds or more of the shelf. Hodgson (1966) found that south of the peninsula, southerly swell is dominant, with a south-easterly component subdominant. The dominant swell period for the area varies from 5 to 12 s, shorter period swell usually being associated with local weather, such as south-west gales in Foveaux Strait.

Refraction of swell is so intense, according to Hodgson, that ". . . swell from the south runs on to the coast . . . with the wave fronts parallel to the shoreline" (p. 81). He further suggested that south-west gales are likely to reinforce southerly swell such that wave height increases and wave period decreases. In such circumstances the effect of refraction on long-period swell is partly overcome and a component of north-easterly longshore drift should persist near to, and parallel to the coast. Southerly swell also is likely to reinforce the offshore tidal current and the Southland Current, so that during and immediately following southerly storms, current velocity is temporarily high.

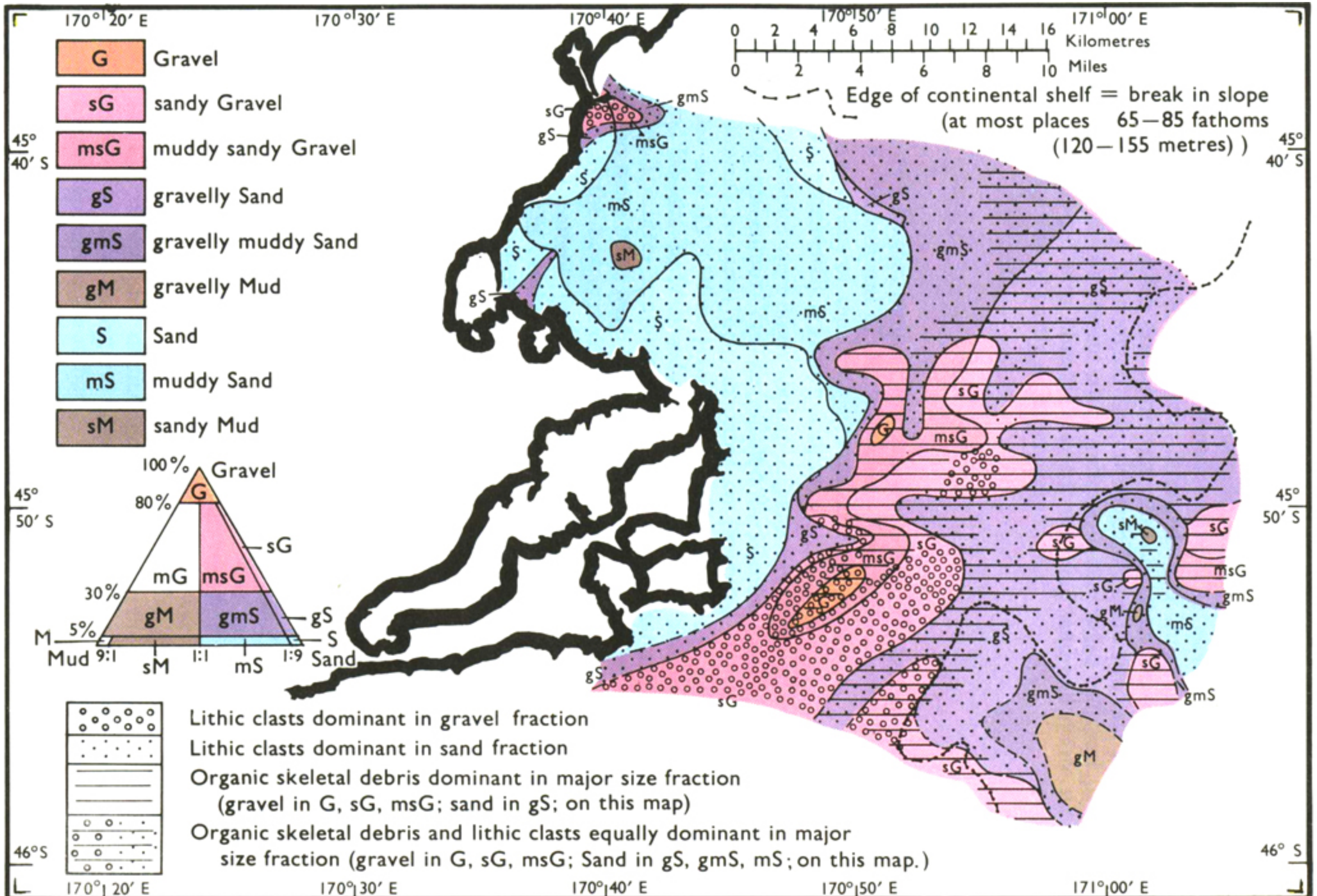

FIG. 4—Bottom sediment distribution showing both texture and gross composition.

North of the peninsula, southerly swell becomes so attenuated during refraction, according to Hodgson, that the sea is commonly flat. In the absence of strong southerly swell the prevailing north-east winds are often responsible for the seas running in Blueskin Bay. The waves are typically short-period (2–6 s), are incompletely refracted, and thus run obliquely inshore. Hodgson concluded that north-east seas may cause limited north to south beach drift along Warrington Spit, although his grain size data suggest the reverse. However, the present study indicates a shoreward transport path from east or north-east into Blueskin Bay for very fine sand and coarse silt. The north-east seas may be partly or largely responsible.

SEDIMENTS

Sampling

A total of 163 bottom samples was analysed (Fig. 3). Eighty were collected by Dr E. Batham and Mr K. Westerkov (Portobello Marine Biological Station) during studies of the benthic fauna, and the remainder along lines of latitude at approximately 2·4 km spacings.

All but 15 samples were taken with an Agassiz trawl. The trawl, designed to sample the epibenthos, can be adapted to simultaneously sample the surficial sediment. A metal box, mounted on the trawl runner, opens via a rectangular slot (9×5·5 cm) to the sea bottom. As the trawl is towed over the sea bottom, surficial sediment is skimmed off and packs into the box (capacity 1·5 litres approximately). The obtained sample represents a trawl track no more 90 m long, and commonly much less. The water-washed upper 2·5 cm in the box is rejected and the remainder retained for analysis.

The sampling pattern has proven sufficiently dense to bring out the significant changes in benthic fauna and sediment character across the area. After analysing approximately 120 samples, it was possible to accurately predict the sediment character of the last 40 samples. The shelf is well covered, from close inshore at minimum depths of 5 m, out to the upper continental slope. In addition, Papanui Canyon has been satisfactorily sampled, though not in any systematic way. Scattered samples only were recovered from other canyons.

Sediment Analysis

Samples were treated with 10% H_2O_2 to remove carbonaceous material. Grain size distribution was determined by dry-sieving and pipette methods, according to procedures detailed by Folk (1965) and summarised in Van der Lingen (1968). The 1–4ϕ interval (medium-very fine sand) was sieved into 0·25ϕ fractions; the remainder of each sample was analysed at 0·5ϕ intervals. Cumulative frequency curves were drawn for the whole sample (skeletal organic debris plus detrital grains) and for the detrital fraction alone. Copies of a table listing the grain size characteristics of all samples analysed are available from the author.

Sediment Chart

Figure 4, summarises the variation in sediment texture over the area. Textural classes are based on the relative proportions of gravel, sand, and mud size fractions according to the Folk *et al.* (1970) classification. The whole sample enters into the calculation. Gravel-size shells of the living gastropods *Zethalia* and *Antisolarium* form a small percentage (1–5% by weight) of the inshore sand, yet do not represent clastic particles. By making 5% gravel the boundary between gravelly and non-gravelly sediment, they were excluded in determining the appropriate textural class. Hence the slightly gravelly sediment textural classes of the Folk *et al.* classification are not recognised herein. No Otago Shelf samples that contain detrital pebbles fall into the expanded non-gravel classes

Percent gravel is plotted on the chart and the data contoured at 0%, 30%, and 80%, the boundaries separating the four classes, gravel-free, gravelly sand and mud, sandy and muddy gravel, and gravel respectively. The percent sand in the sand and mud fraction is plotted on an overlay and the data contoured at 10%, 50%, and 90%, the boundaries separating mud, sandy mud, muddy sand, and sand respectively. The intersecting contour systems define areas, each of which is occupied by a particular textural class.

Two suites of shelf sediments are distinguished, an inner suite that is dominated by sand and muddy sand, relatively free of organic skeletal debris, and an outer shelf suite dominated by gravel, sandy gravel, and gravelly sand, rich in organic skeletal debris.

The inner shelf, from the shallowest depths sampled out to 36 m, east of the peninsula, and to 15–27 m in Blueskin Bay, is covered with hard-packed, micaceous, fine sand (sand class of Fig. 4). Live gastropods and foraminifera dominate the organic skeletal fraction, which commonly forms 2–5% of the sediment. At a few stations, the gastropod *Zethalia* is so abundant that the sediment plots as a gravelly sand.

In Blueskin Bay, hard-packed sand grades seaward into micaceous, silty very fine sand (muddy sand of Fig. 4). In the southern margin of Blueskin Bay and off Taiaroa Head, the sediment is silty fine and medium sand. Organic skeletal debris commonly comprises 3–6% of the sediment. Live gastropods and foraminifera again are characteristic. Silty sand mostly occurs at depths of 18–36 m, although at two places its easterly limit occurs at 49–55 m.

To the north-east, the muddy sand passes into small patches of micaceous very fine sand or gravelly very fine sand in which the gravel fraction consists largely of pelecypod shells. Skeletal debris forms 10–20% of the sediment.

In the vicinity of Cape Saunders the inshore sand grades directly seaward into a narrow band of gravelly sand. Pelecypod and gastropod shells comprise most of the gravel fraction, although small percentages of detrital granules also occur. Organic skeletal debris commonly forms 10–20% of the sediment. The sand fraction is either medium or fine sand. The gravelly sands are transitional to the gravels that predominate in the southern part of the area.

Seaward of the sediments described so far, the organic skeletal debris content rises sharply. Over the entire middle and outer part of the continental shelf more than 40% of the surface sediment is organic debris. In some large patches it forms 60–93% of the sediment (Fig. 5). Only in the

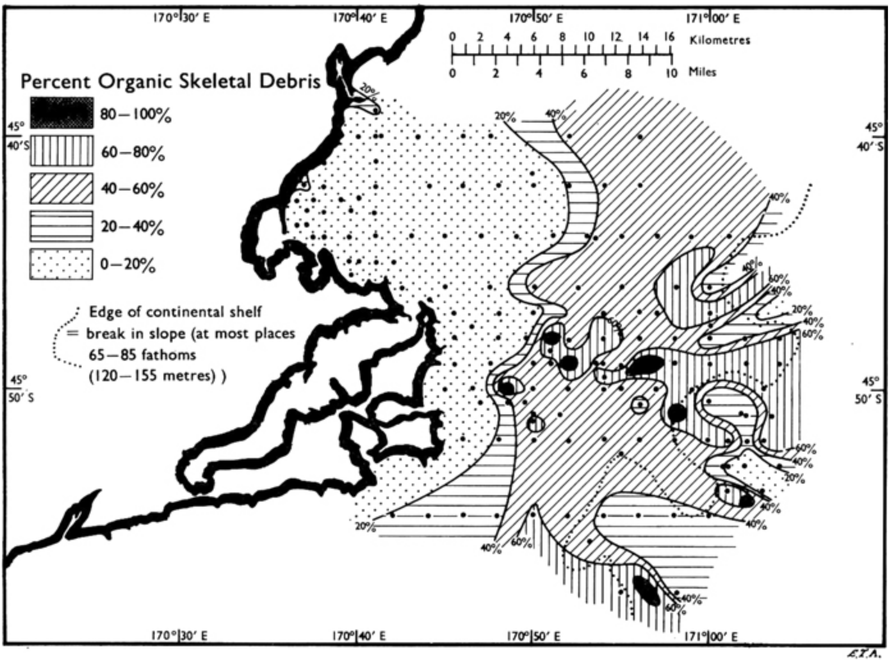

FIG. 5—Distribution of organic skeletal debris as a percentage by weight of the bottom sediment. Compare with Fig. 4.

south, where quartz-pebble gravel predominates, is skeletal debris less prominent.

The most significant sediment is the pebble gravel that occurs at between 55 and 110 m in the southern and central part of the area. The gravel occurs in three textural classes (gravel, muddy sandy gravel, and sandy gravel) that appear to be closely related, and thus are discussed as one. In the south, the gravels consist of very coarse and medium sandy fine and very fine pebble gravel. The pebbles are yellow to cream, well-rounded, rod-like and spherical clasts of quartz and quartzite. The pebbles are smooth where not covered with epizoa. Bryozoa and serpulid worm tubes are the dominant epizoa, and completely cover the coarsest pebbles. As pebble size decreases, the proportion of pebble surface covered by epizoa decreases exponentially, so that most very fine pebble and granule size particles are epizoa-free.

As the gravels are traced northwards, the percentage of detrital pebbles decreases and the percentage of organic debris rises proportionately. Immediately east of Cape Saunders, the band of detrital pebbles splits into two tongues, one extending a short distance further north about the 66 m line, the second the same distance about the 90–100 m line (Fig. 6). The inshore tongue grades north into skeletal gravels composed of bivalves, turritellid

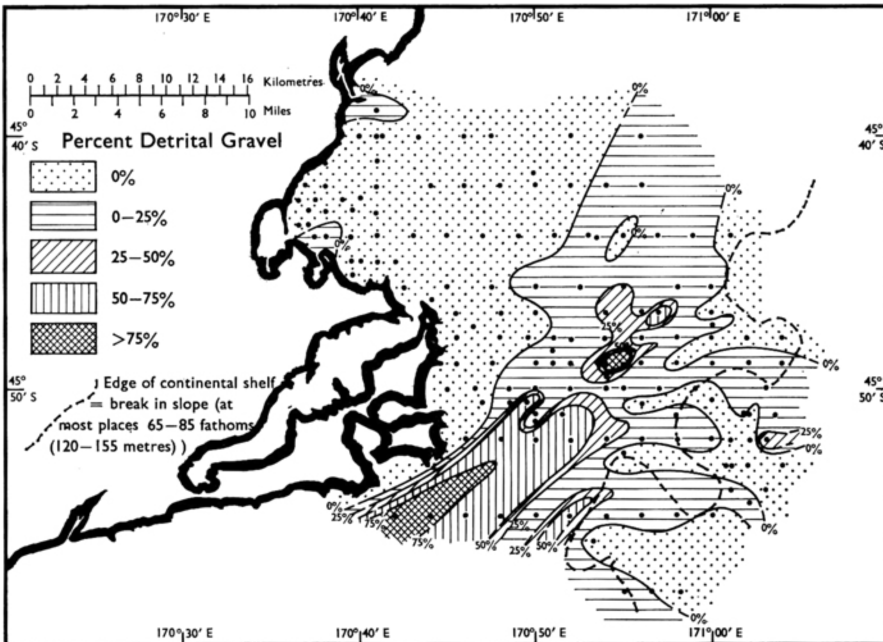

FIG. 6—Distribution of detrital gravel (coarser than —1ϕ) as a percentage by weight of the detrital fraction of the bottom sediment.

gastropods, and bryozoa. The sand fraction of the organic gravels is dominantly fine and very fine sand that consists of detrital grains and foraminifera plus pelecypod fragments. The mud fraction of the muddy sandy gravel is detrital silt. Immediately east of Wickliffe Bay, the outer tongue of fine and very fine quartz pebble and subordinate organic debris gravel grades north into organic debris gravel rich in bryozoa. The sand fraction largely consists of very coarse detrital sand and mixed detrital and pelecypod-foraminifera medium sand. A little further north, at 90 m, organic debris gravel grades into a patch of coarse and fine pebble gravel. The sand fraction of this patch consists of detrital very coarse sand and mixed detrital and organic fine sand. In turn, this anomalously coarse detrital material grades north into organic debris gravel rich in bryozoa. Very fine pebbles of quartz are subordinate. The sand fraction is dominated by fine sand, a mixture of detrital and organic debris.

The gravels grade directly north and north-west into gravelly muddy sand, which in turn grades landward into the muddy sand prominent in Blueskin Bay (Fig. 4). The gravelly muddy sand occurs approximately within the 36–72 m depth range, and consists of organic pebble, silty fine and very fine sand. The organic debris is dominated by bivalves, turritellid gastropods and foraminifera. The sand and silt fraction is dominantly detrital, though in the outer part of the zone organic and detrital fractions are equally abundant. Occasional granules of quartz occur.

The middle shelf sediments grade seaward and north-eastward into gravelly sand, which extends to the edge of the continental shelf and over the upper slopes of the canyons. Again organic skeletal debris forms a major fraction of the sediment (Fig. 5), and consists largely of bryozoa and minute bivalves in the shallower part of the zone, and turritellids, foraminifera and minute bivalves in the deeper part. Granules, very fine, and fine pebbles of detrital quartz are subordinate both in the sediment adjoining the mid-shelf pebble gravels, and in three narrow tongues that extend eastward to the edge of the shelf (Fig. 6). Coarse pebbles of probable Tertiary mudstone (exposed nearby ?) are scattered through the upper slope sediments, particularly in the vicinity of Papanui Canyon.

At some places, especially in an area adjoining and including the upper slopes of Saunders Canyon, the sand fraction of the outer shelf gravelly sand is dominated by comparatively well-sorted detrital fine sand. Elsewhere, the sand fraction consists either of subequal amounts of organic debris and detrital material, or largely of organic debris. Such sands are poorly sorted, coarse to fine, medium to fine, or coarse and fine sand. Foraminifera and pelecypods predominate in the fine sizes, while bryozoa and gastropods are additional prominent components in the coarser fractions.

Small patches of sandy gravel and muddy sandy gravel that are composed largely of organic debris, adjoin the gravelly sand on the upper slopes of the canyons. A very large patch of sandy gravel that adjoins Saunders Canyon, includes a localised tongue of fine pebble quartz and bryozoa gravel. Elsewhere the sandy gravel patches largely consist of bryozoa and subordinate amounts of pelecypods, and gastropods. The sand fraction varies from moderately sorted detrital medium-fine sand, to poorly sorted very coarse–fine sand dominated by pelecypods, foraminifera, and bryozoa.

The middle and lower slopes of the canyons are largely covered by gravelly muddy sand, although dredgings suggest that the sediment forms a discontinuous veneer over Tertiary rock. The gravel fraction consists largely of bryozoa with subordinate pelecypod and gastropod debris, although rare granules of quartz and fine pebbles of probable Tertiary mudstone also occur.

The sediments of Papanui Canyon appear to consist of gravelly muddy sand on the middle and lower slopes, and muddy sand and sandy mud in the canyon axis. Texturally, the sediments consist of silty very fine sand and very fine sandy silt of which organic skeletal debris forms 10–31%. The organic fraction is dominated by mixed benthic and planktonic foraminifera and pelecypods. The sediment distribution pattern shown should be viewed with caution. It only grossly matches the bathymetric outline of the canyon, and is rather simple. The imperfect correlation indicates that the long trawls necessary in dredging fail to accurately sample the complex sediment patterns expected in canyons.

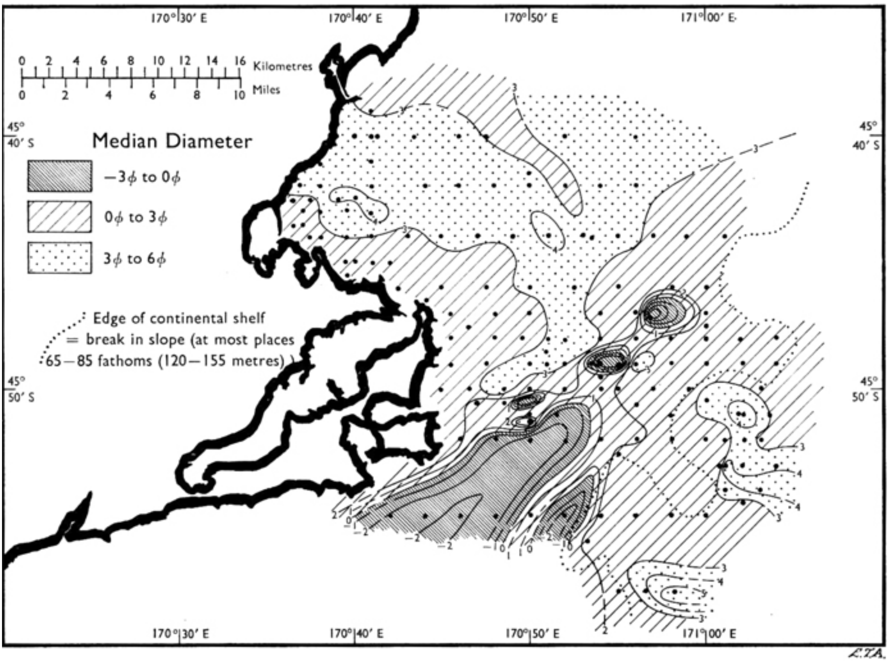

FIG. 7—Geographic variation in median diameter (Mdϕ) of the detrital fraction of the bottom sediment.

Grain Size Distribution

The detrital fraction of the sediments is remarkably polymodal. It commonly consists of a gravel mode and one or more sand modes. Quadrimodal sediment is rare, but trimodal and bimodal sediment is common. Only one third of the samples is unimodal. With the addition of organic skeletal debris to the sediment, grain size distributions become even more complex.

Geographic variation of the Folk & Ward (1957) parameters median, mean, and standard deviation was plotted for the whole sample and for the detrital fraction. Skewness was plotted only for the detrital fraction. Plots are surprisingly systematic, and give consistent patterns of sediment distribution and dispersal (Fig. 7–11).

For plots of whole sediment values, the organic fraction was excluded where it formed less than 30% of the sediment, i.e., the inshore and canyon sand and mud, which at most places contain less than 10% organics by weight. These organics appear to be indigenous rather than transported. Thus for inshore and canyon sand and mud, the same values for median, mean, etc., appear on the plot for the whole sample and on the plot for the detrital fraction only.

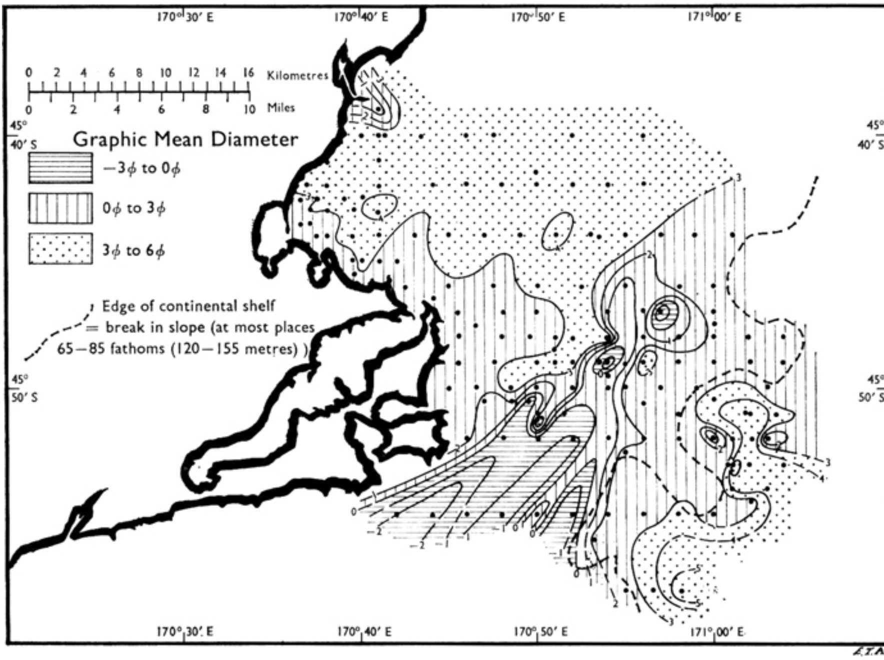

FIG. 8—Geographic variation in graphic mean diameter ($M_Z\phi$) or the detrital fraction of the bottom sediment.

Where organic skeletal debris forms more than 30% of the sediment, the geographic variation in any one size parameter is much the same for the whole sample as for the detrital fraction only. Certainly, the patterns are very similar, even if the values commonly differ. Little additional information is gained by figuring plots for both, and only the mean diameter is reproduced here for both whole sample and detrital fraction.

Plots of median and mean size (Fig. 7, 8, 11) emphasise the prominence of the quartz pebble and quartz+organic pebble gravel tongue that straddles the 73 m isobath. Average clast size decreases regularly landward, seaward, and northward of the gravel tongue. The trilobate character of the gravel tongue, and the fact that gravel content decreases to eventually disappear northward, show that the gravel was distributed from south to north (see Fig. 6).

Fine sand is dominant over both the inner and outer shelf. Very fine sand and coarse silt predominate in Blueskin Bay, in the canyons, and in a V-shaped band extending south between the inshore sands and the gravel tongue.

The plot of median size for the whole sediment (not shown) reveals two additional features: 1. gravel occurs in scattered patches over the upper

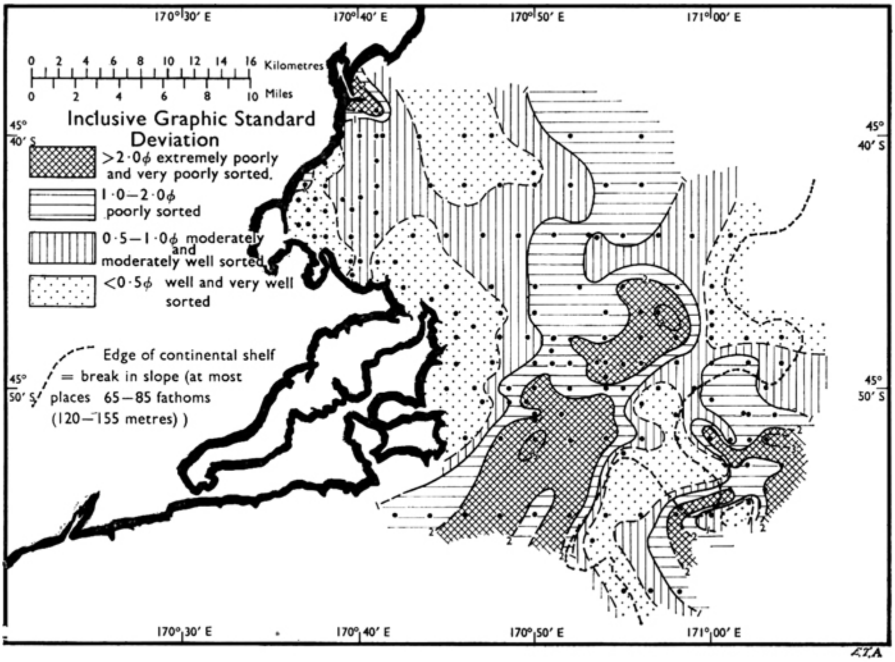

FIG. 9—Geographic variation in inclusive graphic standard deviation ($\sigma_I\phi$) of the detrital fraction of the bottom sediment.

walls of Papanui Canyon; 2. long, narrow tongues of coarse sediment extend from the gravel tongue out to the edge of the shelf, suggesting that dispersal of coarse sediment was not only from south to north, but also obliquely out over the edge of the shelf.

The two plots of standard deviation show very similar patterns, although, as is to be expected, whole sediment values are higher in the pebble and shell-rich areas. The inshore sand, the sand tongue projecting south and south-east from near Karitane Point, and much of the outer shelf sand, are well to very well sorted (0·2–0·5ϕ, Fig. 9). The silty sand of Blueskin Bay and adjoining areas, and the remainder of the outer shelf sand, are moderately well to moderately sorted (0·5–1·0ϕ). The gravel, sandy gravel, and granular sand, which extend north and south over the entire study area about mid-shelf positions, are all poorly to very poorly sorted (1·0–3·1ϕ on the detrital plot). Similarly, the silty sand, sandy silt, and gravelly silty sand of the canyons are poorly to very poorly sorted.

As is to be expected with highly polymodal sediments, skewness values range widely (absolute limits: −0·5 to +0·9) and rather erratically. There is a tendency for inshore sands to be negatively skewed (fine skewed), and for pebble and shell gravels to be strongly skewed, either negatively or positively (Fig. 10).

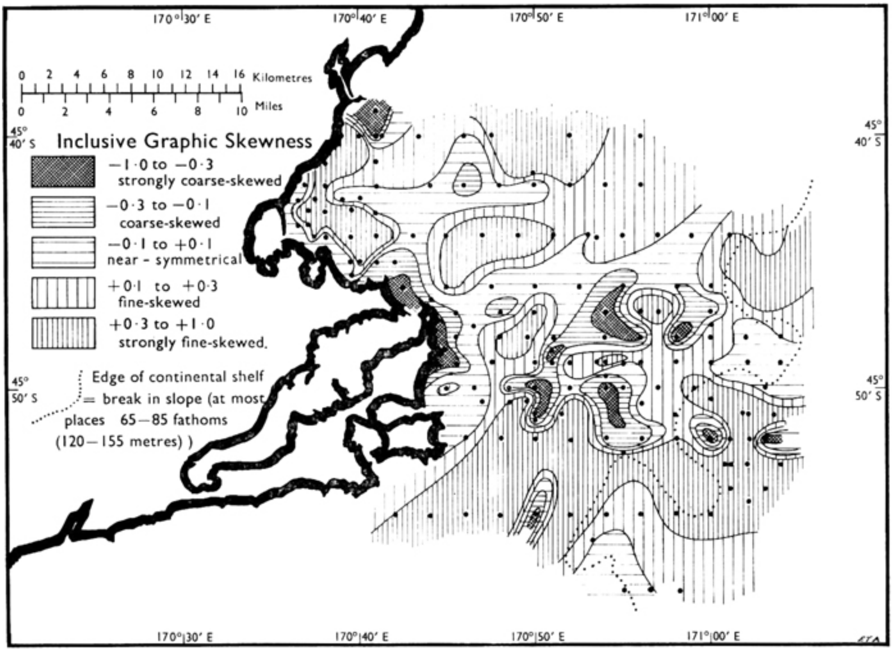

FIG. 10—Geographic variation in inclusive graphic skewness (Sk_I) of the detrital fraction of the bottom sediment.

Sediment Dispersal

The distribution of pebble gravel indicates that the pebbles were introduced into the area from the south (Fig. 6, 8, 11). It was considered that one or more of the size modes in the sand and silt grades might also be traceable over the area, and if so, would show the dispersal directions for part or all of the detrital sand fraction.

Neighbouring modes on a cumulative frequency curve plotted on probability paper are separated by inflection points (Fig. 12). The modal grain diameter for each mode in a sample was determined by finding (by inspection) the 0·1ϕ interval between inflection points that contained the greatest amount of the mode. Modal grain diameters were given to the nearest 0·05ϕ value. A distribution curve (Fig. 13) summarising the frequency of occurrence of the measured modal diameters, and maps showing the geographic distribution of each mode, revealed that five detrital size modes are prominent in the area: I: −4·5 to −2·0ϕ; II: 1·3–2·4ϕ; III: 2·5–2·95ϕ; IV: 3·05–3·4ϕ; and V: 3·95–4·45ϕ.

Mode I (gravel) occurs at 45 stations (Fig. 14). Its distribution confirms that gravel dispersal is from south to north. Its distribution also shows that the transport path (indicated by the zone of coarsest material) straddles

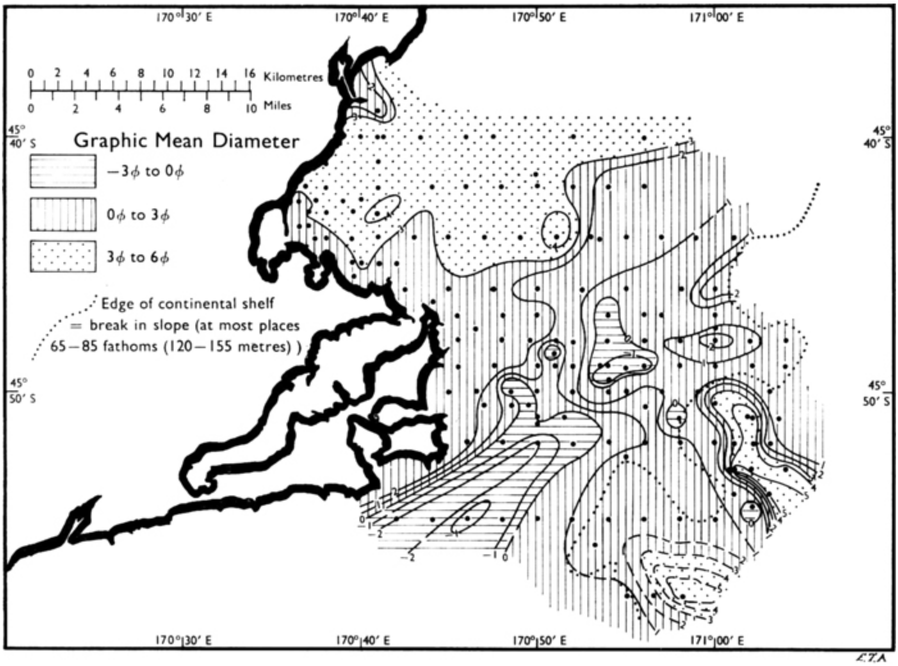

FIG. 11—Geographic variation in graphic mean diameter ($M_Z\phi$) of the bottom sediment (detrital fraction plus organic skeletal debris fraction). Note: where it amounts to less than 30% of the bottom sediment, the organic fraction is disregarded in determining mean values, since it consists very largely of living and recently-living material.

the 90–100 m isobath, and in its southern part lies east of and deeper than the median line of the gravel tongue (Fig. 6). The coarsest gravel (−4·5ϕ, coarse pebbles) is confined to two small patches near the northern limit of detrital pebbles. A second prominent though smaller tongue of gravel occurs inshore of the main tongue. It consists of granule-size clasts. Isolated occurrences of fine pebble gravel occur on canyon slopes.

Mode II (1·3–2·4ϕ, medium to fine sand) occurs at 66 sampling stations (Fig. 15). With the exception of one small tongue of sand immediately east of Taiaroa Head, it is confined to depths greater than 50 m, i.e., middle and outer shelf. Mode II sand is closely associated with mode I gravel, and its dispersal pattern is similar though more intricate. The pattern parallels the isobaths, the coarsest material coinciding with the 90–110 m zone. Modal size diminishes northward, the dominant dispersal trend being in this direction. In addition, the pattern shows a well-developed tendency for dispersal to diverge from the main trend, both inshore towards Taiaroa Head and Blueskin Bay, and offshore towards the shelf edge.

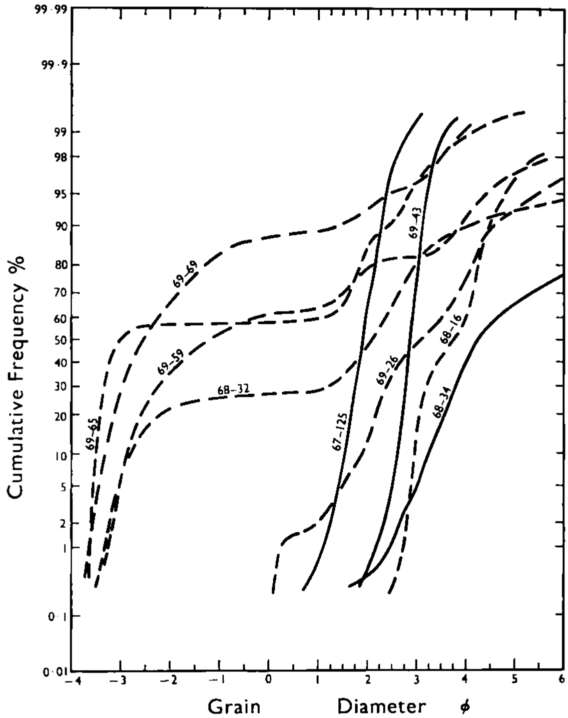

FIG. 12 — Selected cumulative frequency size distribution curves; plotted on a probability ordinate. Broken lines, polymodal distributions; solid lines, unimodal distributions.

Mode III (2·5–2·95ϕ, fine sand) occurs at 80 stations and at all depths (Fig. 16). It is especially prominent inshore, east and north-east of the peninsula, in Blueskin Bay, and over the outer shelf. It is largely absent from the middle shelf and the canyons. The dispersal pattern is complex. In the south, the main line of dispersal lies near the edge of the continental shelf, the zone of coarsest material coinciding with the 110 m isobath. Just north of Saunders Canyon, this dispersal path divides into many diverging paths, one directed north-west and inshore towards Blueskin Bay, and several directed eastward over the edge of the continental shelf. Although mode III is confined to well-defined areas, the coarsest fraction of this mode is patchily distributed. There is rather marked segregation of mode I (gravel) and mode III, although outer shelf mode III overlaps the eastern part of the gravel tongue.

Mode IV (3·05–3·4ϕ, very fine sand) occurs at 42 stations. It is sparsely and very irregularly distributed, but present at all depths. It is rare in the gravels of the extreme south. The main dispersal path is broad, and trends north-north-east over the outer shelf. Again, divergent dispersal inshore brings coarsest mode IV sand right into the shallowest parts of Blueskin Bay.

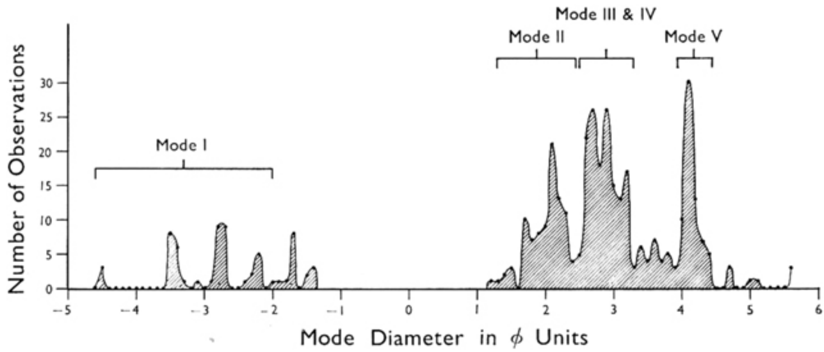

FIG. 13—Distribution curve, showing the frequency of occurrence of the various modal diameters in the 163 bottom sediment samples analysed; detrital fraction only.

Mode V (3·95–4·45ϕ, coarse silt) is present at 50 stations (Fig. 17). With the exception of its isolated occurrence in Papanui Canyon, it is confined to depths less than 110 m, and mostly occurs in depths less than 82 m. It does not occur in the southern gravels. Coarse silt appears to be transported into the area through the shallow waters immediately south-east of the peninsula. From there, the narrow dispersal path trends obliquely across the shelf to depths of 73–82 m. East of Wickliffe Bay, dispersal is deflected north-west and north. Just north of Taiaroa Head the dispersal path divides, some mode V silt continuing northward, the bulk being distributed in an eddy pattern into Blueskin Bay where it predominates. The apparent effect of Otago Peninsula in deflecting the sediment dispersal path somewhat obliquely across the shelf toward deeper water, and in generating secondary landward transport in the lee of the peninsula, is strongly suggested by the dispersal patterns for modes III–V.

Numerous combinations and permutations are possible among the five modes. Certain combinations are prominent, and they are significant in elucidating the depositional history of the area. Half of the total analysed samples have the following characteristics:

unimodal II	–	16 samples
unimodal III	–	28 samples
bimodal III and V	–	17 samples
bimodal IV and V	–	11 samples

All other combinations are infrequent (six samples or less). The geographic association of modes I and II is emphasised by the summary from which the above figures are drawn. No unimodal mode I samples occur, and 38 of the 45 samples that contain mode I also contain mode II, with or without other modes. Five of the remaining seven samples are unique combinations of modes. The very close association of modes I and II is important. It is very likely that mode I and II sediments, which are characteristic of the

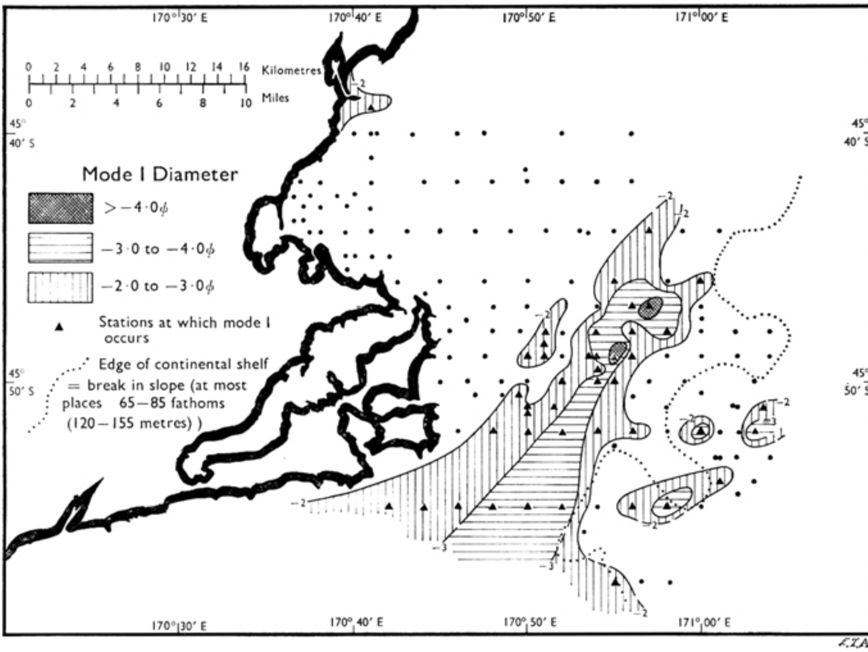

FIG. 14—Distribution and variation in modal diameter of detrital mode I (pebbles).

middle and outer shelf, are relict, presumably Pleistocene. Conversely, modes III–V comprise the inshore sediments of sand, muddy sand, and sandy mud and are presumably Holocene in origin.

Clutha Sediments Sediment distribution over the continental shelf south of Otago Peninsula confirms the dispersal direction and establishes the temporal relationships of the detrital modes.

Data provided by N.Z. Oceanographic Institute, Wellington, suggested that the offshore gravels might be contributed by the Clutha River. Systematic sampling subsequently carried out by r.v. *Munida* in the vicinity of the Clutha, showed that gravel occurs as a continuous band from near the Clutha mouth to just north of Otago Peninsula (Fig. 18). The gravel occurs at mid-shelf positions. It does not extend south of Nugget Point, and its distribution by modal size indicates that the gravel was supplied by the Clutha River. Its distribution also shows that inshore sediments (muddy sand and sand) are progressively burying the gravel. The predominance of epizoan-covered pebbles indicates that the gravel is today rarely in motion, if at all, and that it is probably Pleistocene in origin.

The distribution of other detrital modes through shelf sediments in the vicinity of the Clutha River confirms the fossil nature of the gravels. Modes identical to mode I, II, and III in the Otago Peninsula area occur, along

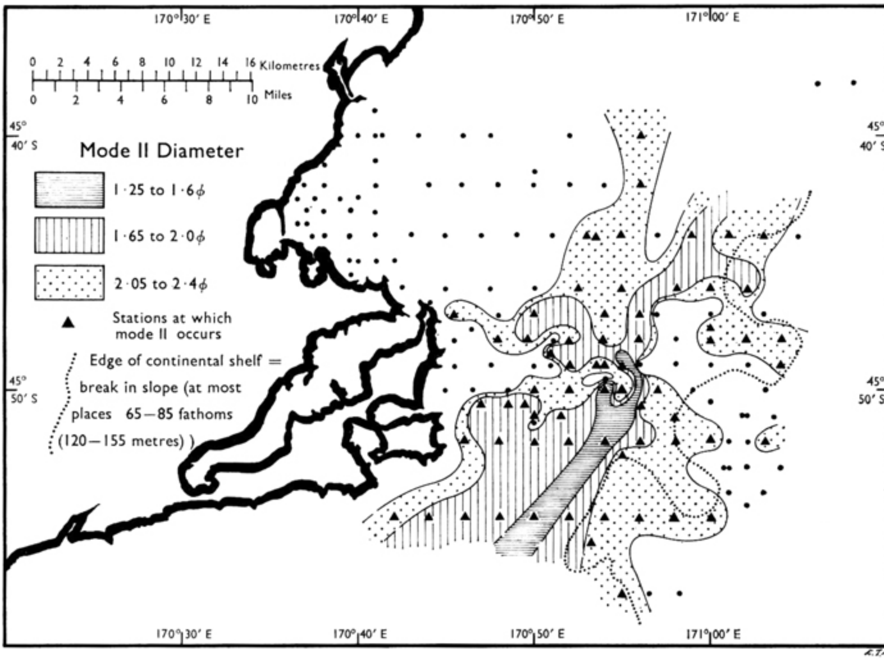

FIG. 15—Distribution and variation in modal diameter of detrital mode II (medium-fine sand).

with a fourth mode that is similar to mode IV and may include mode V. Modes I and II occur in the gravel band. Mode III occurs in the gravel band and in adjoining sands; it forms a pattern centered on Nugget Point, and which appears to discordantly transgress the gravel band. Modes I–III are gradually being buried by Mode IV sediment, which occurs in inner shelf muddy sand and sand. Mode IV currently is being supplied by the Clutha, and its distribution forms a pattern that is discordant with both the gravel band and the mode III pattern. These relationships show that in the Otago Peninsula area mode I and II sediments are oldest and that mode IV and V sediments represent Holocene contributions.

One or two epizoa-free, fine and very fine pebbles occur in some samples of the inner shelf sand and muddy sand close to the mouth of the Clutha (Fig. 18). Apparently at exceptional flood stage, the Clutha still transports fine gravel to the coast, but in insufficient quantities for gravel to cover the sea bottom near its mouth.

Petrography

The detrital gravel consists largely of spherical to rod-shaped clasts; 5–10% are disc-shaped. The clasts are mostly rounded to well-rounded, with the larger grains commonly subrounded (scale of Powers 1953).

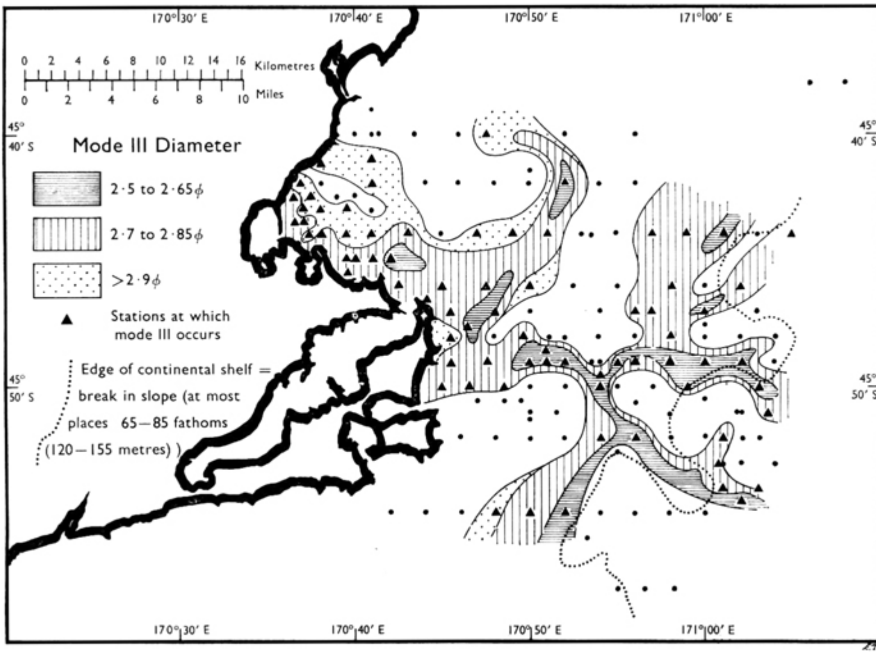

FIG. 16—Distribution and variation in modal diameter of detrital mode III (fine sand).

Approximately 90% of the gravel clasts consist of: 1. yellow to cream quartzite either with medium to coarse-grained granoblastic texture, or with fine-grained xenoblastic texture, and 2. yellow to cream vein quartz consisting of subparallel crystals up to 10 mm long with occasional intergrowths of twinned albite. The remaining gravel clasts are dominantly dark green-grey or grey muddy very fine sandstone (chloritic lithic feldsarenite; terminology follows the Folk *et al.* (1970) classification) with chloritised and sericitised albite, fine grained volcanic and sedimentary rock fragments and radiating intergranular aggregates of stilpnomelane. The quartz, quartzite, and grey sandstone clasts are probably derived from low rank Otago Schists. Rare rounded clasts of dark red-brown medium sandstone (limonite-cemented, ilmenite bearing feldspathic litharenite), and angular clasts of cream or dark brown to black highly altered vesicular volcanic rock, are probably derived from the Permian (?) Waipahi Group of South Otago (Bishop 1965) and from the Dunedin Volcanics (Otago Peninsula and offshore islands) respectively.

The mineralogy of representative samples of the four sand and silt modes shows that each mode also was largely if not exclusively derived from the Otago Schists. Plagioclase (especially albite), rock fragments (especially metamorphic rock fragments), and phyllosilicate minerals are prominent in the

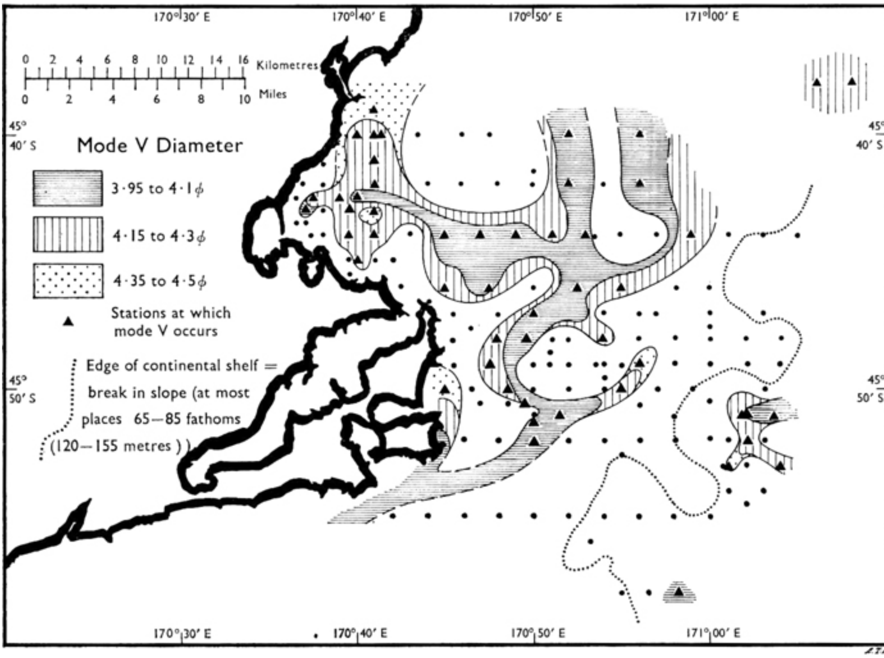

FIG. 17—Distribution and variation in modal diameter of detrital mode V (coarse silt).

light fraction (Table 1), and chlorite group minerals, biotite, zoisite, epidote, hornblende, clinozoisite, and garnet are prominent in the heavy fraction. Sand-size angular volcanic rock fragments, apparently of local origin, are confined to inner shelf sediments near Heyward Point (Fig. 1). They only occur in very coarse to medium sand grades and, hence do not figure in Table 1.

While most detrital sand and silt was probably ultimately derived from the Otago Schists, some has been immediately derived from other rock types. Quartz grains in all size modes are normally clear and very angular to sub-angular, but in mode II sands an additional grain type is prominent: distinctive subangular to rounded grains with yellow surface rind comprise 35% of the quartz grains (Table 2). As concluded by Hodgson (1966) they are probably derived from the Taratu Formation of Cretaceous age that crops out sporadically along the coast south of Otago Peninsula. Their ultimate derivation is the Otago Schists.

BENTHIC FAUNA ASSEMBLAGES

Marine invertebrates contribute vast quantities of whole skeletons and skeletal debris to the surficial sediments. Some of this organic material is living, for example, many of the foraminifera and bryozoa, but much is dead.

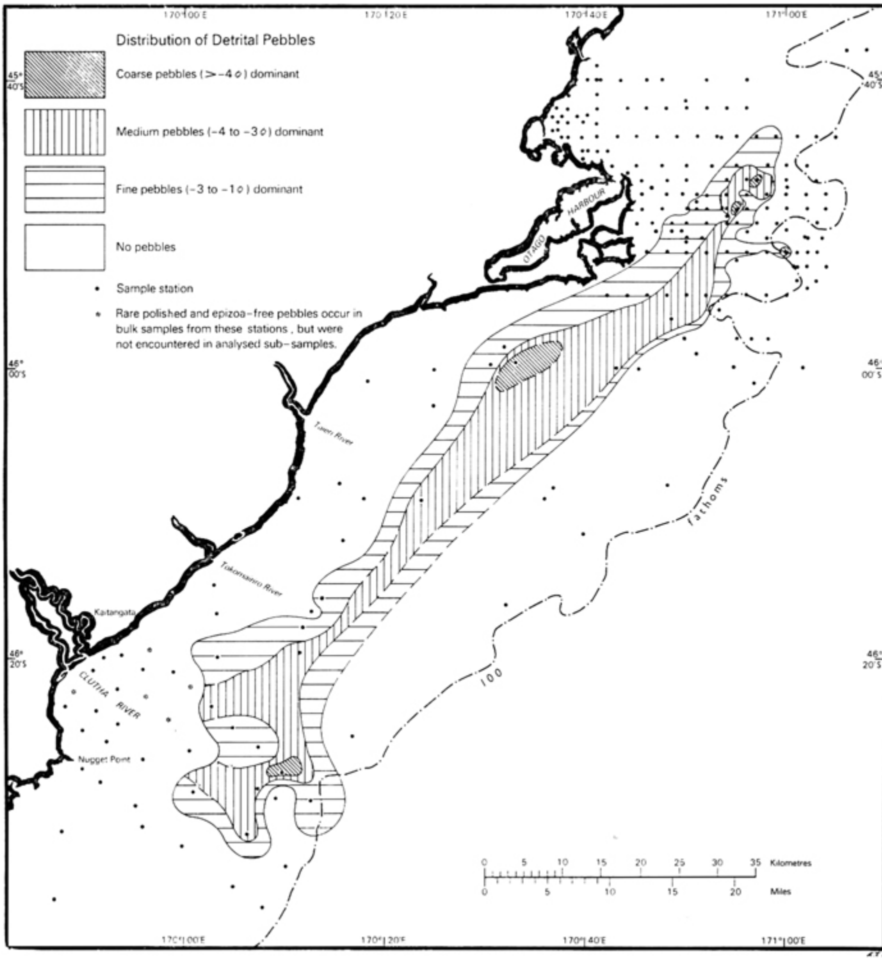

FIG. 18—Distribution of detrital pebbles on the south-east Otago continental shelf, showing their relation to the Clutha River, and their dispersal northward to just beyond Otago Peninsula, (100 fathoms = 183 metres).

TABLE 1—Detrital light fraction composition of samples representing each of the four grain size modes in the sand and coarse silt size range. Proportion expressed as a percentage.

Mineral	Mode II Mu 68–33 1–2ϕ	Mode III Mu 69–54 2·5–3ϕ	Mode IV Mu 69–30 2·75–3·5ϕ	Mode V Mu 66–38 3·75–4·25ϕ
quartz (including single and multicrystal, strained and unstrained grains)	66	49	34	42
K-feldspar (including microcline)	6	5	4	2
plagioclase (largely albite)	12·5	23·5	20	21
indeterminate transparent mins.	0	10	3	3
plutonic rock fragments	2·5	1·5	2	2
sedimentary rock fragments (including chert)	11	1	7·5	2
metamorphic rock fragments	0·5	5	4	8
indeterminate rock fragments	1·5	3	5	9
chlorite	0	1·5	14·5	8
biotite	0	0	2·5	1
muscovite	0	0	3·5	2
heavy minerals (including epidote, zoisite, wollastonite)	0·5	1·5	2	0
grains counted	211	215	216	100

TABLE 2—Roundness of quartz grains in representative samples of mode II (Mu 68–33); III (Mu 69–54); and IV (Mu 69–30) sands. Roundness designations according to Powers (1953) and Folk (1965). (VA = very angular; A = angular; SA = subangular; SR = subrounded; R = rounded; WR = well rounded.)

Sample	Number of grains in each roundness class VA	A	SA	SR	R	WR	Total grains counted	Mean roundness in ρ
mode II, yellow grains	1	11	37	35	26	0	110	3·2
mode II, clear grains	9	40	36	13	2	0	100	2·1
mode III	31	50	18	1	0	0	100	1·5
mode IV	48	50	2	0	0	0	100	1·1

Examination of the skeletal remains in sieved size fractions of the surficial sediments shows that any one taxon in a sample may be represented by living material, by fresh, periostracum-bearing and therefore recently-dead material, and by deeply corroded and bored material that is presumed to be long-dead. In some samples subequal amounts of these three types of material are present, in others one type predominates. Geographic distribution of the long-dead material is largely random. However, living and recently-dead material tends to be dominant in inshore samples, and to a lesser extent in canyon samples.

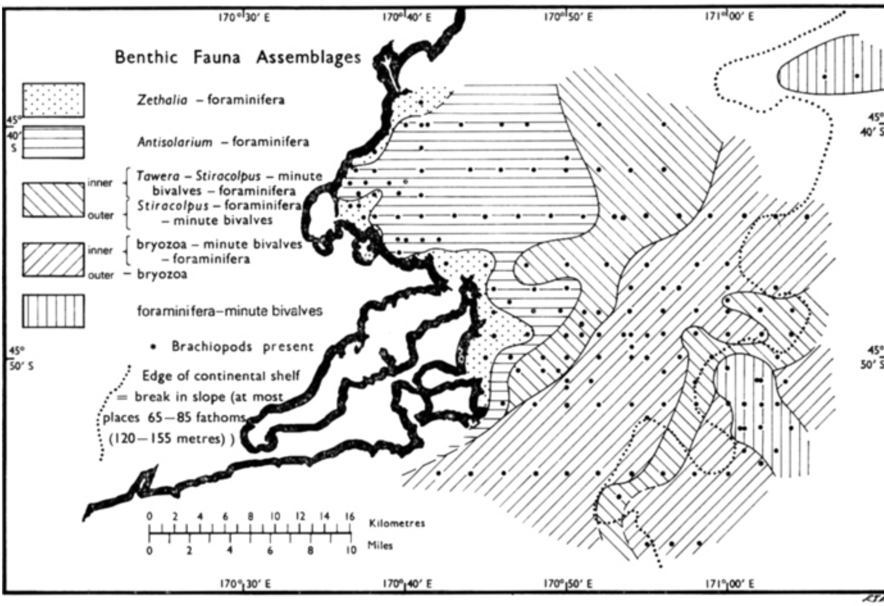

FIG. 19—Distribution of benthic fauna assemblages.

Unless transport of dead skeletal material has been extensive, the organic fraction of each sediment sample gives some guide to the content, diversity, and area of occurrence of the living benthic associations in the area, despite the fact that many generations of any one taxon are present in some samples. Although the organic fraction only includes hard parts, and thus in many instances is not completely representative of the living invertebrate communities that are of zoological interest, nevertheless it is the material that becomes buried with the detrital sediment, and in time, a constituent of the resulting sedimentary rock. For that reason the content and distribution of the skeletal debris is of geological interest.

The taxonomic content of the organic fraction in each of the sieved sediment samples was compiled, and the relative dominance of the phyla and classes determined. A limited range of taxa occur in any one sample, and each sample was readily assigned to one of seven faunal assemblages. Dr A. G. Beu (N.Z. Geological Survey) checked a selection of samples, named the dominant or definitive taxa, and recommended that three inner and mid-shelf assemblages be combined, there being no distinction between them. The five benthic assemblages recognised are geographically restricted (Fig. 19) and apparently representative of living or formerly-living invertebrate associations. Note that whereas the assemblages are designated "benthic", they do include remains of certain planktonic invertebrates, especially foraminifera. Also note that because the observations are based largely on small subsamples (100 gm or less) of the field sample, one or two large invertebrates may not be represented. For example, Dr Beu notes that *Fusitriton,* a large carnivorous gastropod, which is known to occur on the outer part of the Otago Shelf, was not encountered in the subsamples. Further note that a large proportion of the macroscopic material enumerated (Table 3) is fragmentary, and that any one taxon is likely to be represented more by fragments than by whole skeletons.

The assemblages occur over zones that approximately parallel depth contours and crudely match bottom sediment texture. The *Zethalia*–foraminifera assemblage is confined to packed, clean sand, from nearshore out to 10–18 m. *Zethalia zelandica* (A. Adams) and benthic foraminifera are dominant, both living and dead. Other gastropods are scattered throughout, some live, and some represented by juveniles only.

The *Antisolarium*–foraminifera assemblage lies immediately seaward of the *Zethalia*–foraminifera assemblage, and occurs in packed sand and silty sand. It commonly occurs in water depths of 10–27 m, though at one place in Blueskin Bay it appears to extend right to the shore. The assemblage occupies a narrow zone east of Otago Peninsula, but is widespread throughout Blueskin Bay. Live *Antisolarium egenum* (Gould) and benthic foraminifera, such as *Notorotalia* sp., predominate.

The third benthic assemblage occurs over an "inner" zone and an "outer" zone. The "inner" zone is occupied by the *Tawera–Stiracolpus*–minute bivalves–foraminifera assemblage. The assemblage is characteristically associated with muddy sandy gravel and gravelly muddy sand, and over very small areas is also associated with muddy sand, sand, gravelly sand, and sandy gravel. Its depth of occurrence ranges widely from 22 to 95 m, but the assemblage largely is confined to the 36–73 m range. The assemblage is very diverse though dominated by the bivalve *Tawera marionae* Finlay, the gastropod *Zeacolpus (Stiracolpus) symmetricus* (Hutton), by minute bivalves that include *Cosa costata* (Bernard), *C. trigonopsis* (Hutton), *Nucula nitidula* A. Adams, leptonaceans including *Lasaea hinemoa* Finlay, *Cyamiomactra problematica* (Bernard), and Cyamiaceae, and by foraminifera in the finer sand grades.

The content of the "outer" zone of the third assemblage is very similar to that of the "inner" zone; only the relative abundances differ. The "outer" zone is occupied by the *Stiracolpus*–foraminifera–minute bivalves assemblage. With the exception of two occurrences in sandy gravel, the assemblage is confined to gravelly sand. The assemblage occurs on outer shelf and upper slope, and while it occurs over the 110–360 m depth range, it is largely confined to 125–180 m. *Zeacolpus* (*Stiracolpus*) *symmetricus* (Hutton) is dominant, and foraminifera and minute bivalves subdominant. Of the minute bivalves the most common are *Cyamiomactra problematica* (Bernard) and the leptonaceans. Foraminifera predominate in the finer sand grades. One possibly significant feature is the relative abundance of the shallow-water gastropod *Antisolarium egenum,* which is represented by many worn, broken, or juvenile but dead shells.

The fourth assemblage, which is dominated by bryozoa, is also divided into "inner" and "outer" zones. The bryozoa-minute bivalves–foraminifera assemblage of the "inner" zone occurs on gravelly sand, sandy gravel, gravel,

TABLE 3—Composition of the Benthic Faunal Assemblages.

I : *Zethalia*–foraminifera
II : *Antisolarium*–foraminifera
III inner : *Tawera*–*Stiracolpus*–minute bivalves–foraminifera
III outer : *Stiracolpus*–foraminifera–minute bivalves
IV inner : Bryozoa–minute bivalves–foraminifera
IV outer : Bryozoa
V : Foraminifera

(*** dominant, ** subdominant, * common, s sparse.)

	I	II	III		IV		V
			inner	outer	inner	outer	
PELECYPODA							
Nuculidae							
Nucula nitidula A. Adams			**	s	s		
N. sp.						s	
Nuculanidae							
Neilo rugata Dell							s
Glycymeridae							
Glycymeris (*Glycymerula*) *modesta* (Angas)					s		
G. (*Grandaxinea*) *laticostata* (Quoy & Gaimard)			s		s		
G. sp.				s			
Limopsidae							
Austrosarepta benthicola Dell							s
Philobryidae							
Cosa trigonopsis (Hutton)			**			s	
C. costata Bernard			*	s	s		
Philobrya pinctada (Finlay)			s				
P. sp.						s	
Mytilidae							
Lanistina impacta (Hermann)			s				
Modiolus areolatus (Gould)			s				
M. sp.			s				
Pinnidae							
Atrina pectinata zelandica (Gray)					s		
Pectinidae							
Chlamys (*Mimachlamys*) *dichroa* (Suter)						s	
C. (*Mimachlamys*) *dieffenbachi* (Reeve)			s		*		
C. (*Mimachlamys*) *gemmulata* (Reeve)			s				
C. (*Mimachlamys*) *zelandiae* (Gray)			*				
C. (*Mimachlamys*) sp.				s			s
C. (*Zygochlamys*) *delicatula* (Hutton)				*	s	s	
C. sp.							s
Cyclopecten aupouria Powell							s
Limidae							
Escalima regularis Powell				s	s		s
Anomiidae							
Monia zelandica (Gray)			s	*		s	*
Ostreidae							
Ostrea sp.			s		s		
Crassatellidae							
Cuna sp.				s			

TABLE 3—*continued*

	I	II	III inner	III outer	IV inner	IV outer	V
Carditidae							
Cardita aoteana Finlay			s		s		
Venericardia (*Purpurocardia*) *purpurata* (Deshayes)			*	s	s	s	
Pleuromeris zelandica (Deshayes)			**	s	s		
P. marshalli Marwick			s	s	s		
Cyamiidae							
Cyamiomactra problematica (Bernard)			**	**	**	*	
Diplodontidae							
Diplodonta (*Zemysina*) *globus* (Finlay)			s				
D. sp.			s		s		
Thyasiridae not det.			*				
Lucinidae							
Divaricella (*Divalucina*) *huttoniana* (Vanatta)				s			
Leptonidae							
Lasaea hinemoa Finlay			**			*	
Leptonacea not det.			**	*	**		
Montacutidae							
Notolepton antipodum (Filhol)	*	s				*	
Cyamiacea not det.			**		**	*	
Cardiidae							
Nemocardium pulchellum (Gray)			*	s	s	s	
Veneridae							
Dosina zelandica Gray			s				
Dosinia sp.			s	s			
Notocallista (*Striacallista*) *multistriata* (Sowerby)				*		s	
Tawera marionae Finlay			***	*	*	*	
Paphirus largillierti (Philippi)			s				
Tellinidae							
Tellinella sp.			s				
Semelidae							
Leptomya retiaria (Hutton)			s				
Sanguinolariidae							
Gari stangeri (Gray)			s				
G. sp.			*				
Ascitellina urinatoria (Suter)			s	*	s	s	
Mactridae							
Maorimactra ordinaria (Smith)	s						
Scalpomactra scalpellum (Reeve)				s		s	
Hiatellidae							
Hiatella arctica (Linnaeus)			s		s		
Panopea sp.						s	
Corbulidae							
Caryocorbula zelandica (Quoy & Gaimard)			s				
Myochamidae							
Myadora antipoda Smith						s	
M. novaezelandiae Smith				s			
M. subrostrata Gray			s				
M. sp.				s			
Hunkydora australica novozelandica (Reeve)			s				
Indeterminate pelecypoda	*	*	*	**	**	*	*

	I	II	III inner	III outer	IV inner	IV outer	V
GASTROPODA							
Fissurellidae							
Emarginula striatula (Quoy & Gaimard)			s	s			
Trochidae							
(Trochinae)							
Trochus (*Coelotrochus*) *huttoni* (Cossmann)			*		s		
Micrelenchus caelatus (Hutton) subsp.			*	s			
M. sp.					s		
(Calliostomatinae)							
Maurea sp.			s	s		s	
Umboniidae							
Antisolarium egenum (Gould)	s	***		**	s	s	
Zethalia zelandica (A. Adams)	***		*		*		
Turbinidae							
Argalista fluctuata (Hutton)				*	*		
Modelia granosa (Martyn)			s				
Rissoidae							
Estea micronema (Suter)					s	s	
E. rufoapicata (Suter)				*	s	s	
Haurakia sp.					s		
Rissoidae not det.				s			
Eatoniellidae							
Eatoniella sp.					s		
Cerithiidae							
Zaclys sarissa (Murdoch)				s			
Lyroseila chathamensis (Suter)			s		s		
Triphoridae not det.			s	s			
Turritellidae							
Maoricolpus roseus (Quoy & Gaimard)			*		s		
Zeacolpus (*Stiracolpus*) *symmetricus* (Hutton)	s	*	**	**	*		
Z. (*Stiracolpus*) apex indet.							s
Epitoniidae							
?*Opalia* sp. or ?*Acrilla* sp.				s			
Calyptraeidae							
Sigapatella novaezelandiae (Lesson)			s				
Zegalerus tenuis (Gray)			s				
Maoricrypta (*Zeacrypta*) *monoxyla* (Lesson)			s		s		
Naticidae							
Tanea zelandica (Quoy & Gaimard)			s			s	
T. sp.			s				
Proxiuber australis (Hutton)							s
P. sp.					s		
Naticidae indet.			s				s
Muricidae							
Zeatrophon ambiguus (Philippi)			s				
Z. caudatinus Finlay			s		s		
Z. imetus Finlay				s			
Xymenella pusilla (Suter)			s				
X. sp.				s	s		
Xymene plebius (Hutton)	s						

TABLE 3—*continued*

	I	II	III inner	III outer	IV inner	IV outer	V
Muricidae—*continued*							
Axymene cf. *corticatus* (Hutton)			s				
A. sp.			s	s		s	
Comptella coronata Dell				s			
Terefundus sp.				s	s		
Columbellidae							
Zemitrella sp.			s	s	s		
Liratilia aff. *gracilis* Powell					s		
L. conquisita (Suter)			s				
Buccinulidae							
Buccinulum sp.			s	s			
Euthrenopsis venusta (Powell)				s			
?*Penion* sp. or ?*Aeneator* sp.			s				
Neptuniidae							
Austrofusus glans (Roeding)			s				
Cominellidae							
Cominella (*Eucominia*) sp.			s		s		
Columbariidae							
?*Coluzea* sp.							s
Volutidae							
Alcithoe (*Leporemax*) *fusus* (Quoy & Gaimard)			s				
Marginellidae							
Marginella (*Volvarina*) *albescens* (Hutton)				s		s	
Turridae							
Aoteadrillia wanganuiensis (Hutton)			s	s			
Splendrilla hermata Dell				s			
Mitrithara gemmata (Suter)				s			
Neoguraleus sinclairi (Gillies)			s				
Antiguraleus pulcherrimus Dell							s
A. sp.			s				
Liracraea otakauica Powell				s			
Retusidae							
Retusa pachys (Watson)				s	s	s	
?*Retusa* sp. or ?*Cylichnina* sp.							s
Scaphandridae							
?*Scaphander* sp.							s
Pyramidellidae not det.	s		s	s			
Agatha georgiana (Hutton)				s			
Indeterminate gastropoda		s		*	*		s
AMPHINEURA							
Cryptoconchidae							
Craspedochiton rubiginosus (Hutton)			s				
SCAPHOPODA							
Siphonodentaliidae							
Cadulus sp.							s
BRYOZOA	s	s	*	*	***	***	s
FORAMINIFERA	**	**	*	**	*		***

	I	II	III inner	III outer	IV inner	IV outer	V
OTHER GROUPS							
Sponge fragments			*		s	s	
Scleractinian coral							s
Polychaete opercula		s					
Polychaete tubes			s	*	s	s	
Brachiopoda				*	*	s	s
Arthropoda							
crustacean fragments			s	s			s
cirripede fragments			*	*			
Balanus decorus Darwin			s				
Echinoid fragments		s					s

and the outer part of the area of muddy sandy gravel. It is largely confined to depths of between 65–120 m, although its extreme limits are 45–365 m. The bryozoan element, which is completely predominant, consists of fragments of solid, clumped colonies, hemispherical colonies, and thin, mat-like forms. Minute bivalves, including cyamiaceans such as *Cyamiomactra problematica* (Bernard) and leptonaceans, are predominant in the very fine pebble and coarse sand fractions. Crushed mollusc shall of indeterminate taxonomy, and quartz pebbles and coarse sand appear to have comprised the substrate upon which the assemblage became established.

Bryozoa comprise 60–90% of the coarse fraction of samples from the "outer" zone of the fourth assemblage, and only in the coarse sand fraction do minute molluscs and foraminifera occur in any quantity. For this reason, the assemblage is identified simply as a bryozoa assemblage. It occurs on the upper continental slope between Saunders and Papanui Canyons at depths of 125–365 m approximately, where the bottom sediments are predominantly sandy gravel and gravelly sand. At least 60% of the bryozoa are long, slender, much-branched forms, in contrast to the clumped to hemispherical colonial forms characteristic of the "inner" zone. Apart from the contrast in bryozoa, the content and diversity is very similar to that of the "inner" zone.

The fifth assemblage is a foraminifera assemblage that is confined to the canyons. It is largely associated with muddy sand and sandy mud, and in depth ranges from 180 to more than 730 m. Few molluscs are associated with the foraminifera; they largely consist of indeterminate fragments. Fragments of scaphopods echinoid spines, and scleractinian coral, which appear to be absent elsewhere, occur in very small amounts.

No work has been done on the foraminifera, except to record abundances in relation to other groups. Ostracods are widespread and are represented by numerous taxa (Swanson in prep. "The ostracod faunas of the Otago Shelf, New Zealand").

Living and recently-dead brachiopods also show a well-defined distribution pattern (Fig. 19). They are confined to the middle and outer shelf in the south-eastern part of the area, in depths of 55–180 m, and are associated with pebble and organic debris gravel, sandy gravel, and gravelly sand exclusively. Although indeterminate brachiopod fragments predominate, whole *Magasella sanguinea* and *Neothyris* sp. cf. *lenticularis* were recovered at 4 of the 13 brachiopod stations.

Origin of Sediments Rich in Organic Skeletal Debris

Wherever they occur, high concentrations of organic skeletal debris in middle and outer shelf positions probably represent condensed depositional sequences that reflect ". . . a reduction in the amount of sediment reaching the distal regions of the shelf, following the rapid post-glacial rise in sea level" (Cullen 1970, p. 15). In the relative absence of detrital sediment, the skeletal remains of successive generations of invertebrates gradually accumulate to form organic debris-rich deposits. Such deposits also may include skeletal remains of shallow-marine organisms relict from a Pleistocene low stand of sea level. For example, individual molluscs that normally live at 25–45 m were recovered by Cullen from 106–126 m in the Foveaux Strait area. They gave radiometric dates of 8–10 000 years B.P.

The corroded, extensively-bored, and commonly abraded mollusc shells of the *Tawera–Stiracolpus* and bryozoa-dominated assemblages on the Otago Shelf are presumed to be long-dead and therefore relict. At first sight, the parallel repetition of the *Tawera–Stiracolpus* assemblage and the bryozoa assemblage in "inner" and "outer" zones (Fig. 19) on the Otago Shelf suggests that the "outer" zone of both assemblages formed when sea level was much lower than at present, and the "inner" zone when sea level was at either its present-day level or some intermediate level. The relative abundance of the shallow-water gastropod *Antisolarium egenum* in the "outer" zone of the *Tawera–Stiracolpus* assemblage lends support to the suggestion.

On the other hand, there is no obvious mixing of depth–controlled communities or individuals (P. A. Maxwell, N.Z. Geological Survey, pers. comm.). Apart from *Antisolarium,* all taxa come from depths that they range over today. This fact, plus the presence of living, recently-dead, and long-dead representatives of a taxon in many samples, suggests the middle and outer shelf assemblages reflect present-day sea levels, and reflect accumulation of successive generations of skeletons in the relative absence of detrital sediment. In addition, the parallel repetition of the *Tawera–Stiracolpus* and bryozoa-dominated assemblages can be accounted for by the modern hydrology. The "inner" zone of the bryozoa-dominated assemblage, with its solid, clumped to hemispherical colonies, is coincident in position with the core of the Southland Current. The "outer" zone, with its slender, much-branched bryozoa, occurs over the upper continental slope and edge of the shelf, where water agitation is commonly greater than for middle and outer shelf areas (Sverdrup *et al.* 1942; Van der Linden 1969). It is reasoned that the *Tawera–Stiracolpus*–minute bivalves–foraminifera assemblage is the usual assemblage at mid and outer shelf depths, but that where water agitation is high, with all its ecological implications, the bryozoa-dominated assemblages supplant it.

My conclusion, endorsed by Dr Beu and Mr Maxwell, is that the distribution of benthic faunal assemblages over the Otago Shelf is consistent with the modern hydrology and depths, but that the assemblages largely consist of varying proportions of recently-dead and long-dead material.

HISTORY OF SEDIMENTATION

Many aspects of the Otago Shelf sediments can be accounted for by the modern hydrology. The distribution of benthic fauna assemblages appears to be related to present-day sea level and coastal current patterns. The assemblages occupy zones that approximately parallel depth contours and crudely match bottom sediment texture. The distribution of the five detrital size modes (Fig. 14–17) is consistent with dispersal by the Southland Current in mid and outer shelf positions, and by a combination of eddy currents (related to the Southland Current) and longshore drift (induced by refraction of southerly swell) over the inner shelf. Similarly, various expressions of average size (viz median, mean), despite the polymodality of the detrital fraction, show that the sediment was distributed from south to north by the Southland Current.

The tongues of pebble gravel are unrelated to submerged shorelines, which they transgress (Fig. 2). Dispersal and accumulation of these gravels must therefore postdate development of the shorelines, which presumably were formed during lower stands of sea level, and must be considered in terms of the modern hydrology. Similarly, sediment patterns and distribution patterns of mode III and mode V sediments obliquely cross the drowned spit east of Blueskin Bay (cf. Fig. 1 and 4; and Fig. 1, 16, and 17 respectively). If the spit is still growing, distribution patterns should parallel its length.

In contrast, other features do not reflect the modern hydrology and must, in part or in whole, be considered relict. Obviously, the drowned shorelines reflect sea levels much lower than the present-day. That they remain unburied by sediment also suggests that sedimentation rates subsequently have been slow. Also, whereas the distribution of the five detrital size modes is consistent with dispersal by the Southland Current, the Clutha area evidence is that the modes are separated both in time and space. Mode I–III sediment is presently being buried by mode IV and V sediment which is being contributed by the Clutha River. In the sense that mode I–III sediment predates mode IV and V sediment, the former does not exactly reflect present day environmental conditions and therefore is relict. It is also the sediment in which modes I–III predominates that is rich in organic skeletal debris, debris that includes numerous successive generations of taxa representing a considerable span of time.

In the Otago Peninsula area the gradation seaward from nearshore sand to muddy sand, to muddy sandy gravel and gravelly muddy sand (mid shelf), to mud-free gravels and sandy gravels (middle and outer shelf), is consistent with wave controlled sediment winnowing related to present-day sea level, as occurs in wave-dominated seas such as the Gulf of Mexico. Wave action selectively removes mud from shallow sediments to produce clean sand. Muddy sand accumulates in deeper water where winnowing is progressively less effective. The finest silt and clay is held in suspension and settles in deeper water where wave motion is ineffective. In the Otago Peninsula area fine silt and clay, winnowed from nearshore areas, is slowly spreading over the mid-shelf skeletal debris and pebble gravels to produce the muddy sandy gravels and gravelly muddy sands. This conclusion supports both the relict nature of middle and outer shelf organic and pebble-rich sediments, and a Holocene age for the inshore organic debris-free sediments. The relative absence of mud on the outer half of the shelf may reflect Southland Current turbulence.

All aspects of the Otago Shelf area can be satisfactorily accounted for, although at first sight many conflict. The preferred explanation, to a large extent follows Emery's (1968) interpretation of the U.S.A. Atlantic continental shelf Quaternary sequence. This sequence consists of acoustically transparent units averaging 20 m thick, which are interpreted to be fine-grained sediments deposited during interglacial stages of high sea level. Each unit is separated by a thin, acoustic reflecting horizon that is interpreted to represent coarse-grained coastal plain and shoreline sediments that are reworked to form a transgressive sand sheet during rising sea level. On the Otago shelf, the mid-shelf sandy gravels represent the transgressive sand sheet, whereas the inshore muddy sands and sands represent the first accumulation of the fine-grained sediment that is deposited during interglacial high sea level conditions.

During the early part of the rising sea level stage following the last glaciation, increased meltwater run-off apparently led to increased competency and capacity of the Clutha River. Pebble gravel and medium sand (mode I and II sediment) was supplied to an ever-submerging continental shelf. As water depth increased, the Southland Current moved on to the shelf reworking the pebbly sand and sandy gravel and gradually transporting it northward. As sea level continued to rise, the current presumably moved progressively further on to the shelf, the locus of pebble gravel transport and accumulation similarly moving westward. The net effect through time would be to produce a multi-lobed sheet or band of gravel, with more and less extensive lobes developing as the rate of sea level rise varied. Eustatic curves by Suggate (1968) and Cullen (1970) suggest that rates of sea level rise did vary. East of Otago Peninsula, the pebble gravels do form a trilobate, in part discontinuous band, the seaward lobe of which consists of coarse gravel, and the innermost of which at places consists of the finest gravel (Fig. 6, 7, 8, and 14).

Other aspects of Otago Shelf sediment distribution may well be related to specific changes in the rate of sea level rise. Suggate's eustatic curve suggests that at about 8–9000 years B.P. near-stillstand existed, with sea level at approximately −20 m. Cullen's curve shows a temporary fall in sea level (−12 to −18 m) at 8000 years B.P. It is very likely that during any such temporary stillstand or minor reversal in sea-level rise, aggradation of the lower reaches of the inflowing rivers reached such a state that each river was no longer competent to transport coarse sediment to the coast, except perhaps under extreme flood conditions. It appears that at a time such as this, perhaps 8–9000 years B.P., mode I (gravel) and mode II (sand) no longer was regularly carried to the coast. Instead mode III sand became the normal contribution and it was gradually spread across the shelf, beginning to bury mode I and II sediment. Mode III sand must have been distributed northward by the Southland Current during the rapidly rising sea level phase that occurred between 8000 and 5500–6000 years B.P. (Suggate 1968; Cullen 1970). Since then it has continued to be redistributed in reduced quantities over the outer shelf by the Southland Current, and probably in larger quantities into Blueskin Bay by wave-induced longshore drift and back-eddy currents related to the Southland Current system.

It is likely that the drowned spit east of Blueskin Bay formed during the 8–9000 years B.P. stillstand (Suggate) or fall in sea level (Cullen). The crest of the spit regularly declines in elevation towards the distal end. The decline is possibly a consequence of spit development during falling sea level. Such an interpretation best fits Cullen's observations.

Modal distribution of sediment off the mouth of the Clutha River indicates that during the standing sea level stage (*c.* 6000 years B.P. to present), mode IV and ?V has been deposited over the inner shelf to the virtual exclusion of mode III sediment. East of Otago Peninsula, mode IV and V sediment has, and continues to be transported by longshore drift and particularly by back-eddies of the Southland Current system. It is being mixed with mode III sediment, which probably is being reworked from the southern reaches of the Otago Shelf.

The distribution of benthic faunal assemblages is interpreted to be related to existing shelf morphology and depths. In the sequence of events inferred above, the assemblages therefore must have become established during the last 6–9000 years B.P. In this sense, the assemblages in fact represent epifaunal benthic communities.

CONCLUSIONS

1. Otago Shelf detrital sediment is distributed by the Southland Current. Coarse sediments (modes I and II—pebble gravel and medium sand) were supplied and redistributed by the current during the early to middle phase of the post glacial rise in sea level. Mode III (fine sand) was supplied as a consequence of a temporary halt in sea level rise that occurred about 8–9000 years B.P. It was distributed by the Southland Current and is probably being reworked northward by the current today. Mode IV and V sediment (very fine sand and coarse silt) is presently being distributed, largely by the Southland Current, and to a limited extent by longshore drift. Apparently it is being supplied as a consequence of the post 6000 years B.P. stillstand in sea level.

2. Drowned shorelines are recognised at *c.* −120 m, *c.* −90 m, and *c.* −60 m. At −21 to −27 m a drowned spit occurs, which is interpreted to mark another temporary shoreline. Each shoreline presumably reflects a

temporary halt in post-glacial sea level rise. The shoreline at −60 m compares with Cullen's (1970) −65 m shoreline in Foveaux Strait (dated at *c.* 10 000 years B.P.), and the −21 to −27 m spit roughly coincides with his temporary sea level fall at 8–9000 years B.P. Detrital sediment transgresses these shorelines and therefore post-dates their origin. The persistence of each attests to the relatively slow rate of post-glacial sedimentation.

3. In the period since sea level attained approximately its present level, sediment has accumulated extensively over the inner shelf, but only extremely sparsely over the middle and outer shelf. Inner shelf sediment texture generally reflects depth, with sand inshore grading to muddy sand offshore, a gradation which implies that winnowing by wave action is effective inshore and less effective offshore.

4. At approximately 45 m, inshore detrital sediments give way to sediments rich in organic skeletal debris (40–90% of any bottom sample), which is mixed with pebble gravel at mid-shelf positions in the southern part of the study area. Much of the skeletal debris-rich sediment is relict.

5. The distribution of benthic faunal assemblages is consistent with present-day shelf morphology, depths, and likely zones of turbulent water. The numerous generations of any one taxon present in middle and outer shelf assemblages simply reflects the long period of time during which Holocene detrital sediment has been excluded from these areas of the shelf (at least the last 6000 years).

6. The Southland Current is deflected obliquely across the shelf towards the continental slope by the Otago Peninsula. As a consequence, spill-off or back-eddies in the lee of the Peninsula become important in sediment dispersal close inshore. Similar hydrologic systems should exist in the vicinity of other East Coast, South Island promontories, such as Banks Peninsula.

7. The detrital sediment is predominantly derived from the Otago Schists; minor amounts are derived from Permian and Mesozoic sedimentary rocks; trace amounts are from Tertiary volcanic rocks exposed locally along the coast.

8. The detrital sediment is supplied predominantly by the Clutha River, whose drainage basin extends to western Otago and is developed almost entirely in the Otago Schists. This study does not show if the coastal rivers Tokomairiro and Taieri contribute sediments. If they do, their contribution is likely to be small since their courses are extensively aggraded.

9. The use of modal size to determine the dispersal paths and source points of detrital sediment has proved to be valuable.

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Drs R. Carter and C. Landis, University of Otago, provided me with a copy of Dr P. Marshall's 1931 report to the Otago Harbour Board "On Soundings and Dredgings off Otago Harbour", to date the most complete investigation of Otago Shelf sediments. I have not drawn from this report, which only became available towards the end of my investigations. It is to be regretted that it has not been formally published. At the date of its submission, 23 April 1931, it would have borne favourable comparison with any other investigation on shelf sedimentation. Dr Marshall's approach and reasoning would still be applied in coastal investigations today.

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