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THE SUBMARINE GEOLOGY OF FOVEAUX STRAIT

By

DAVID J. CULLEN

New Zealand Oceanographic Institute

Memoir No. 33

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FRONTISPIECE View westward across Toetoes Bay and Foveaux Strait to Stewart Island, from Fortrose. The estuary of Mataura River in foreground; Waituna Lagoon and low-lying peat marsh beyond; with the hills of Bluff Peninsula forming horizon in right half of the photograph. *Photograph—Whites Aviation Ltd.*

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FOREWORD

In the morphology and sediments of the continental shelf lies a significant part of the record of late Pleistocene events, particularly those related to fluctuations of sea level.

It has become clear that present-day sedimentary processes have not obscured the past environments in most areas, though they may be substantially changed. In anomalous shelf areas such as Foveaux Strait where tidal current velocities are high, deposition of finer grade sediments under present conditions can be inhibited or profoundly modified. The present memoir demonstrates the utility of such circumstances in allowing the reconstruction of late Pleistocene geologic events.

J. W. Brodie
Director,
N.Z. Oceanographic Institute

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HISTORICAL NOTE

For many years following the discovery of New Zealand, the narrow channel that separates Stewart Island from the South Island land mass remained unknown. James Cook, in his circumnavigation of New Zealand between 1769 and 1770, rejected his first observations and assumed the discontinuity in the coastline in the vicinity of the channel to be merely a deep embayment.

> 'And now we thought that the land to the Southward, [Stewart Island] or that we have been sailing round these 2 days past, was an Island, because there appeared an Open Channell [Foveaux Strait] between the N. part of that land and the S. part of the other in which we thought we saw the Small Island [Ruapuke] . . . but when I came to lay this land down upon paper from the several bearings I had taken, it appeared that there was but little reason to suppose it an Island. On the contrary, I hardly have a doubt but what it joins to, and makes a part of, the Mainland.'[1]

For 38 years after, mariners acting upon Cook's conclusions sailed round Stewart Island.

While it is probable that the existence of the Strait was known to local sealers and whalers during the latter years of the eighteenth century, it was not until March 1809 that the discovery of the Channel was officially notified and the Strait named, when a notice appeared in the Sydney Gazette 'Ships News' of that month:

> 'Yesterday arrived from the Southward the *Governor Bligh,* colonial vessel, Mr Grono Master . . . In a new discovered Strait which cuts off the South Cape of New Zealand from the mainland, fell in about the middle of February with the *Pegasus,* Captain Bunker . . . In the Strait abovementioned, which is called Foveaux Strait, the *Pegasus* struck upon a rock but received very little damage, and the *Governor Bligh* met a like accident, though with no material damage.
>
> The above Strait Mr Grono describes as:
>
> 'being from about 36–40 miles in width, and a very dangerous navigation from the numerous rocks, shoals and little islands, with which it is crowded.'[2]

At the time of departure of the *Pegasus* and *Governor Bligh* the name Foveaux was topical in Sydney. Lieut. Col. Joseph Foveaux had arrived from England in July 1808, and finding the Governor of New South Wales deposed and under arrest, he assumed command of the colony until the dispute was settled.

On early charts the channel was referred to as Foveaux's Strait, a usage eventually abandoned in favour of the modern form.

One of the first to describe Foveaux Strait in any detail was M. Jules de Blosseville, a senior midshipman aboard the French Expedition vessel *Coquille.* From information and diaries obtained from captains of sealing vessels he compiled a description of the New Zealand coast.[3] He compared the configuration of Foveaux Strait with that of Bass Strait but commented that currents were much stronger in Foveaux Strait, the most dangerous passage being between Centre Island and the mainland where "the flow and ebb rush through with a speed of as much as five to six miles".

[1] Cook, J. 1893: Captain Cook's Journal during his first voyage made in H. M. Bark "*Endeavour*" 1768-71, edited by Captain W. J. L. Wharton, R.N., F.R.S. Elliot Stock, London, lvi, 400 pp.

[2] McNab, R. 1907: Murihiku and the Southern Islands. William Smith, Invercargill, New Zealand; xiii, 377 pp.

[3] Blosseville, J. de. 1907: [Sealing activities around Foveaux Strait] *In* McNab, R., Murihiku and the Southern Islands. William Smith, Invercargill, xiii, 377 pp. (McNab states translated from Nouvelles Annales des Voyages, Tome 29, Paris, 1826).

THE SUBMARINE GEOLOGY OF FOVEAUX STRAIT

by

David J. Cullen

ABSTRACT

Foveaux Strait, separating the South Island of New Zealand from Stewart Island, has a smooth, almost featureless floor lying at an average depth of 15 fathoms, and standing above the open shelf to the east and west. Remnants of a pre-Flandrian shoreline along the eastern margin of the Strait, at a depth of approximately 35 fathoms, indicate that, at the end of the Pleistocene period, terrestrial conditions prevailed over the region now occupied by the Strait.

Certain of the sediments in the Strait confirm the former existence of a terrestrial environment, and in the submarine gravels palimpsest fluviatile dispersal patterns are distinguishable by petrographic and statistical analyses of the constituent pebbles.

Shell beds are widespread in Foveaux Strait, hence biogenic calcareous detritus is important in many of the sediments. Carbonate analyses, combined with particle-size analyses, allow recognition and comparison of the sedimentological behaviour of the calcareous and rock/mineral components transported by traction, saltation and suspension.

INTRODUCTION

PREVIOUS WORK (1951-65)

Despite the importance of Foveaux Strait as the site of an old-established oyster fishing industry, and the relevance of submarine morphology and bottom sediments to the ecology of the oyster (Cullen, 1962), no systematic regional investigation of the bathymetry and sediment distribution in the Strait has previously been undertaken. Fleming's (1952) description of typical sediment from one of the oyster beds remains the only significant contribution in this field.

Other studies include a description by Couper (1951) of the microflora of a lignite sample, recovered from a depth of 9 fm in Toetoes Bay by HMNZS *Lachlan*, and Wood's (1958) account of the geology of a small area in Bluff Harbour, based upon a number of exploratory submarine drill cores. More recently, there have been petrological studies of beach sands from a number of points along the north shore of Foveaux Strait (Martin and Long, 1960; Martin, 1961).

SCOPE OF PRESENT SURVEY

In 1960, the New Zealand Oceanographic Institute initiated a detailed benthic study of the Strait with an extensive sampling programme. Working with m.v. *Viti*, between the 20th May and 10th June 1960, bottom sediment samples were collected from a total of 54 stations distributed throughout the Strait, and short cores were obtained at a further three stations (fig. 1). Analysis of these samples forms the basis for the ensuing account of the composition, distribution and provenance of the bottom sediments. Several samples collected in Paterson Inlet have not been utilised in the present study. There are also a number of sediment samples collected by HMNZS *Lachlan* during her hydrographic survey of Foveaux Strait. Because of their small size and the method of collection (by Worzel sampler) these are unsuitable for full analysis and have not been used.

The bathymetry of the Strait, upon which the interpretation of submarine morphology is based, has been compiled exclusively from data supplied by the Hydrographic Branch, Navy Department, in the form of "collector sheets' of closely spaced lines of soundings (Cullen, 1965).

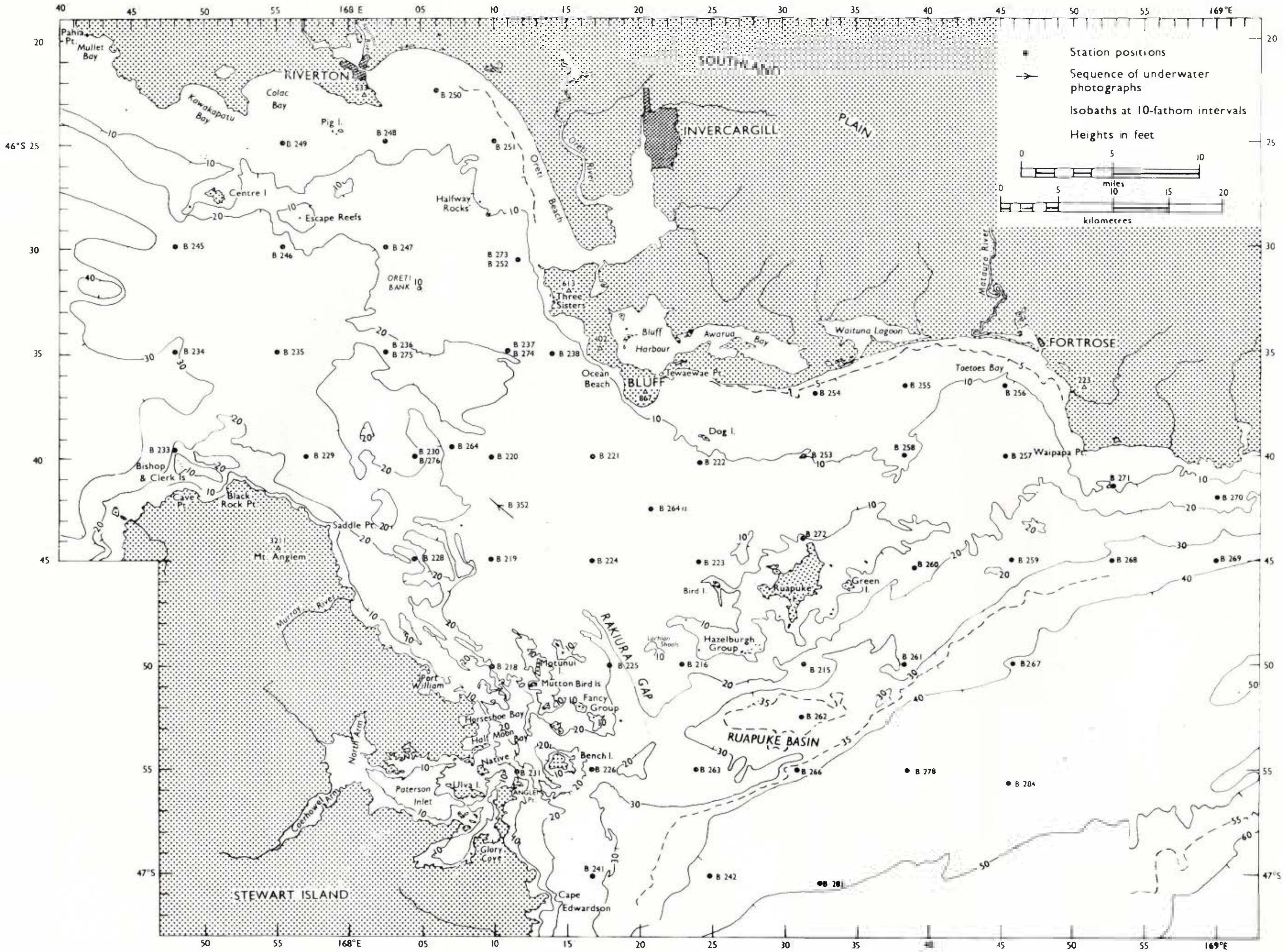


FIG. 1 Map of Foveaux Strait, showing station positions, simplified bathymetry, and localities mentioned in the text. Depths in fathoms, at 10-fathom intervals Heights in feet above high-water springs.

PHYSICAL CHARACTERISTICS OF THE STRAIT

GEOMORPHOLOGY AND DEVELOPMENT

Foveaux Strait covers approximately 950 square miles at the southern extremity of New Zealand, where it separates the South Island from the small rugged mass of Stewart Island. In the description that follows, the western limit of the Strait is arbitrarily fixed at longitude 167° 43′E, and a line between Waipapa Point on the mainland and Cape Edwardson on the east coast of Stewart Island denotes its eastern boundary (fig. 1). The Strait, which is approximately 50 miles long, follows a somewhat sinuous NW-SE course bounded by roughly parallel coasts. At its narrowest, between Three Sisters and Saddle Point, the channel is a mere 14½ miles in width, broadening to 22 miles at its western entrance and reaching a maximum of 33 miles between Waipapa Point and Cape Edwardson.

The topographic contrast between the opposing coasts of Foveaux Strait is quite marked, reflecting a considerable dissimilarity in their geologic character. Stewart Island, consisting entirely of massive igneous and metamorphic crystalline rocks, rises steeply from sea level to reach a height of 3211 ft on Mount Anglem, only 2 miles from the coast. The relief of the mainland to the north of the Strait is much more subdued, with level plains underlain by unconsolidated Quaternary gravels extending several miles inland at heights of less than 100 ft above sea level. The low-lying northern coastline is interrupted, however, by the isolated rocky promontory of Bluff which rises 867 ft above the plains (plate 1).

SOUTHERN SHORELINE

The northern and north-eastern coasts of Stewart Island, which form the southern shore of the Strait, are typical immature, crenulate shorelines of submergence with rocky, cliffed headlands and deeply indented coves (such as Halfmoon Bay and Horseshoe Bay) backed by pocket beaches. The north-eastern coast shows a closer approach to linearity than the remaining coastline of the Island, perhaps partly because it lies parallel to, and may be influenced by, the NW – SE regional structural trend, and partly because of its sheltered position with respect to the prevailing south-westerly winds (Watts, 1947).

PATERSON INLET

Opening into the south-eastern corner of the Strait is Paterson Inlet, a shallow, branching, and almost completely enclosed stretch of tidal water that penetrates far into the centre of Stewart Island. Hemmed in by steeply rising hills, notched at the water's edge by low, almost vertical cliffs, the inlet provides a perfect example of an ancient river system that has become inundated to form a ria.

The entrance to Paterson Inlet is obstructed by a number of small rocky islands, some linked to the mainland by mature or incipient tombolos, barring the inlet from the open sea except for a narrow channel between Anglem Point and Native Island. The long, narrow rocky isthmus leading to Anglem Point must have existed formerly as a chain of small islands, the original channels to the open sea, ESE of Ulva I. and through Glory Cove, being now sealed by simple tombolos.

At the head of Paterson Inlet and extending further inland along the North and Caerhowel Arms are broad deltaic mudflats, traversed by narrow tidal channels.

NORTHERN SHORELINE

The physical features of the shoreline north of the Strait are quite different from those of the Stewart Island coast. Although limited stretches of steep, rugged coast do occur between Pahia Point and Riverton in the west, on Bluff promontory, and near Fortrose at the eastern end of the Strait, they are separated by the wide sweeping, curved embayments of Oreti Beach and Toetoes Bay (frontispiece, plate 2).

This northern coast can be considered of contraposed type and entering a mature stage of evolution, in that it owes its configuration basically to preferential erosion of unconsolidated Quaternary deposits from around upstanding masses of ancient solid formations (Plates 1-4). A tendency towards smoothing out of coastal irregularities by local progradation is evident along the northern shore, being marked in the region between Fortrose and Bluff by the development of a series of sand and shingle spits. Bay-mouth

PLATE 1 View eastward from Bluff, showing rock outcrops at Tewaewae Point on the far side of the harbour entrance, Awarua Bay to the left, and Toetoes Bay in the distance on the right. Note the low-lying coast and hinterland.
Photograph—Whites Aviation Ltd

PLATE 2 View north-west along Oreti Beach, showing the low-lying coast and hinterland. The Longwood and Takitimu ranges occupy the middle distance to the left, the snow-clad mountains of Fiordland form the horizon.
Photograph—Whites Aviation Ltd

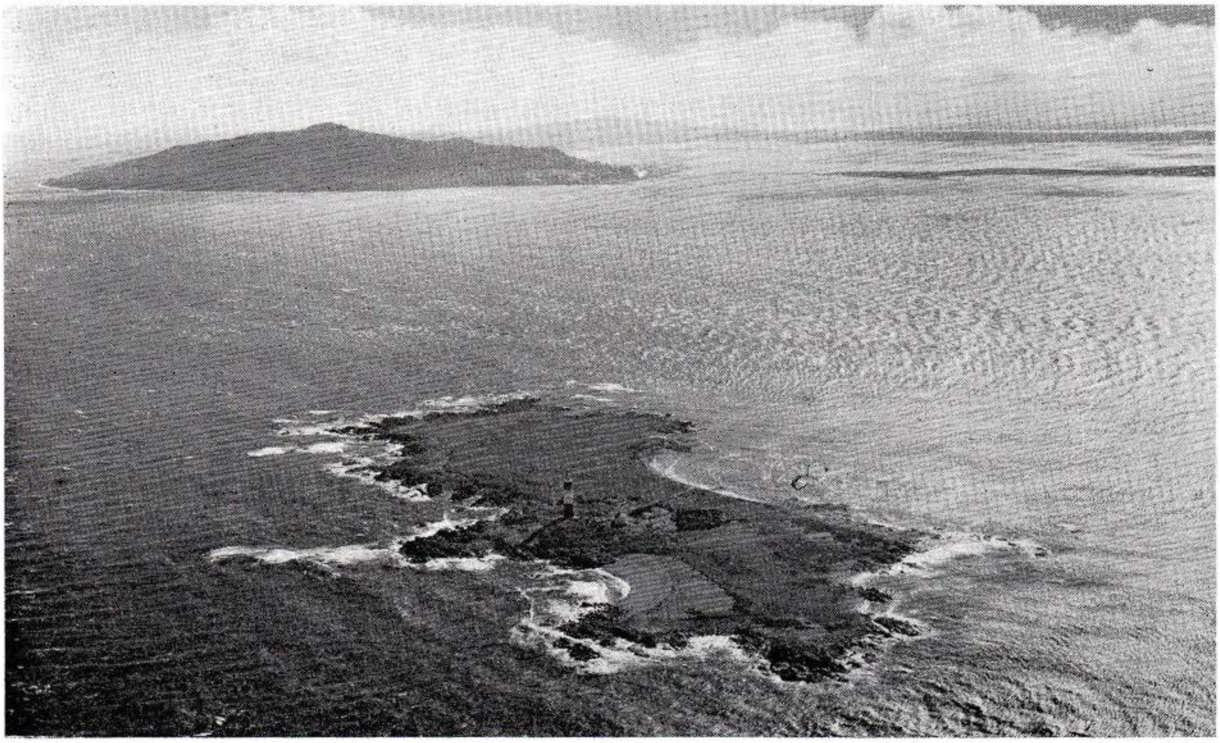


PLATE 3 View across the northern part of Foveaux Strait from Dog Island to Bluff Peninsula and the Harbour. The contrast may be seen between the low-lying coast (horizon at right) formed by the Quaternary deposits and the upstanding mass of ancient solid formations at Bluff Peninsula. *Photograph—Whites Aviation Ltd*

PLATE 4 View south across Colac Bay and Foveaux Strait to Centre Island and (on the horizon) the northern coast of Stewart Island and offshore islands. The headland in the middle distance is composed of ancient solid formations, rising above unconsolidated Quaternary sediments which form the plain in the foreground. *Photograph—Whites Aviation Ltd*

bars, with steep seaward slopes, have formed across the estuaries of rivers that drain into Toetoes Bay, enclosing small lagoons backed by a low-lying hinterland of peat marsh. A much broader spit, capped by sand dunes, encloses Awarua Bay and Bluff Harbour (plate 1).

The direction of growth and the extent of the bars are affected by local variations in the longshore drift. The Mataura River, for instance, has been diverted parallel to the coast for 3 miles by the eastward growth of a narrow spit extending almost as far as Fortrose (frontispiece). However, the adjoining spit, which encloses Waituna Lagoon, has developed over an equal distance in the opposite direction. A remnant of the old shoreline is still preserved along the inner margin of Waituna Lagoon at its eastern end, where a 'dead' sea-cliff composed of unconsolidated quartz gravel rises about 15ft above high-water level.

North of Bluff also, coastal progradation is much in evidence. The course of the Oreti River has been diverted southward by the growth of a broad spit, and its estuary partially choked by extensive mud-flats and salt marsh. The Oreti spit differs from those fringing Toetoes Bay in having a very gentle seaward slope and wide beach, and being backed by a broad zone of sand dunes (plate 2). Viewed from the air, traces of numerous closely-spaced, low ridges can be discerned along the spit, aligned more or less parallel to the shore, and presumably representing former strand lines that mark stages in coastal progradation.

The overall effect of the building-up of spits on each side of the Bluff promontory has been to produce a large-scale coastal feature resembling examples of incomplete double tombolos in western and southern France (Guilcher, 1958, pp. 89-90).

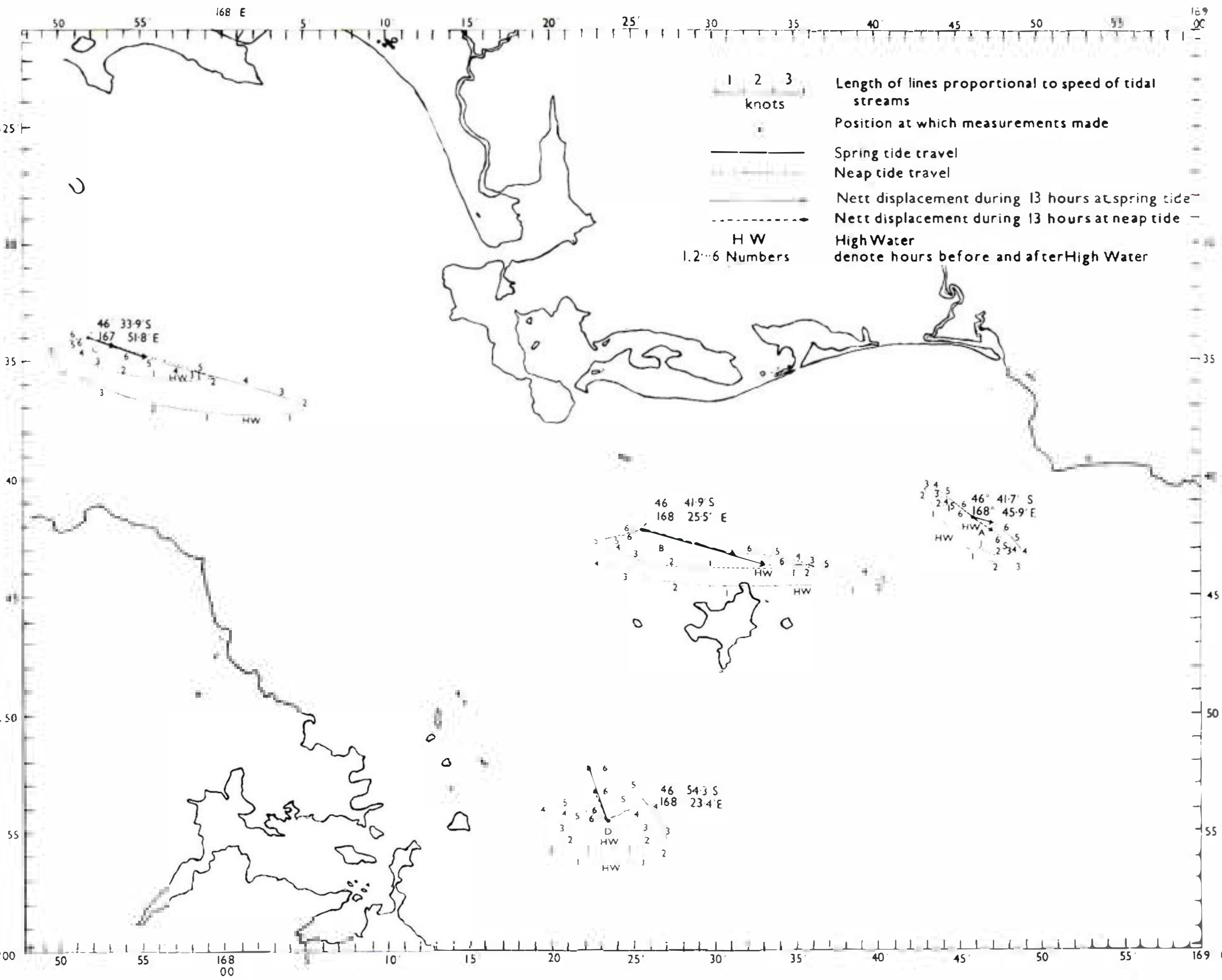


FIG. 2 Map showing current trends at four localities in Foveaux Strait. Constructed from data on Hydrographic Branch Chart NZ 67 (formerly NZ 14).

ISLANDS IN THE STRAIT

Two groups of islands, associated with numerous reefs and small projecting rocks, lie within the Strait. One group extends across its eastern entrance from the vicinity of Paterson Inlet and the other occupies the north-western sector of the Strait. In addition a small cluster of exposed rocks—the Bishop and Clerk Is—lies close inshore in the south-western part of the Strait (fig. 1). Like Paterson Inlet, the islands represent remnants of a drowned terrestrial landscape.

The largest island in the eastern group—Ruapuke—has an indented coast of steep rocky headlands, reaching a maximum height of 207 ft, separated by open sandy beaches. Its eastern shoreline, however, has the form of a developing cuspate foreland, while the general outline of the island suggests that its present morphology results from the linking together of several rocky islets by recent tombolos (see Guilcher, 1958, p. 87).

Bench I., which lies close to the entrance to Paterson Inlet, is the highest island in the Strait, rising to 319 ft above sea level.

HYDROLOGY

Little detailed information is available regarding currents in Foveaux Strait, an unfortunate circumstance in view of the intimate relationship between current activity and the transportation and deposition of sediment. Published data are restricted to a brief commentary on the velocity and direction of tidal streams (in the NZ Pilot, Hydrographic Department, 1958), together with some more specific observations from four widely-spaced stations, published on the Hydrographic Branch chart (NZ 14 now NZ 67) of Foveaux Strait. The latter gives hourly variations in both neap and spring tidal streams, allowing a generalised reconstruction of the current pattern (fig. 2).

In brief, the rising tide sets eastward through the Strait, direction being reversed with the fall of the tide. Although the velocities of the tidal streams do not normally exceed 1.5 knots at springs, higher velocities (up to 2.2 knots) have been recorded in the passage between Bluff and Ruapuke I. and in the western part of the Strait. The NZ Pilot (1958) refers to currents up to 3.0 knots among the islands near the entrance to Paterson Inlet. That the influence of these currents extends to depth and affects sedimentation in the Strait is suggested by the absence of fine detritus from regions where the high-velocity streams operate, while fine sand and even mud occur where the currents are less powerful.

Plotting of the data published by the Hydrographic Branch reveals an eastward mean drift at the three stations in the northern and western sectors of the Strait (fig. 2). This drift is presumably coincidental with the eastward movement of surface waters through the Strait, detected by drift-card studies and named the *Southland Current* by Brodie (1960) and Garner (1961, p. 62). At the fourth station in the south-eastern corner of the Strait the data indicate a localised north-west mean drift, this being perhaps a subsidiary of a current sweeping northward along the east coast of Stewart Island to join the *Southland Current*.

SUBMARINE MORPHOLOGY

The eastern and western geographic limits of Foveaux Strait coincide approximately with bathymetric features that delineate the Strait equally clearly on the basis of submarine morphology.

The floor of the Strait comprises an almost featureless plain, sloping imperceptibly westward from depths less than 10 fm to over 25 fm, and truncated across the eastern entrance to the Strait by much steeper gradients that lead down to the inner margin of the open shelf at about 40 fm (fig. 3A). To the north and south the plain rises towards the confining shorelines, very abruptly in the case of the Stewart Island and Bluff Peninsula coasts (fig. 3D), but with only gentle shelving in Toetoes Bay (fig. 3B) and off Oreti Beach. The off-shore gradient is clearly related to the resistant or unconsolidated nature of the rocks on the adjacent coasts.

The flattest part of the Strait floor extends across the narrow, central region between Bluff promontory and Port William (fig. 3D) the bottom here lying between 15 and 20 fm with gradients averaging about 1 : 1500. Westward, the floor of the channel slopes away gradually, becoming more undulant and seemingly traversed by a system of narrow, tortuous depressions (fig. 1). Steeper slopes are encountered in the vicinity of Centre I. and the Escape Reefs, separating a 5–10 fm platform in Colac and Kawakapatu bays from the deeper (20–30 fm axial region of the Strait to the south (fig. 3E). Eastward, the submarine plain rises to depths of less than 10 fm, the bottom topography becomes more diverse with numerous steep rock pinnacles, and a chain

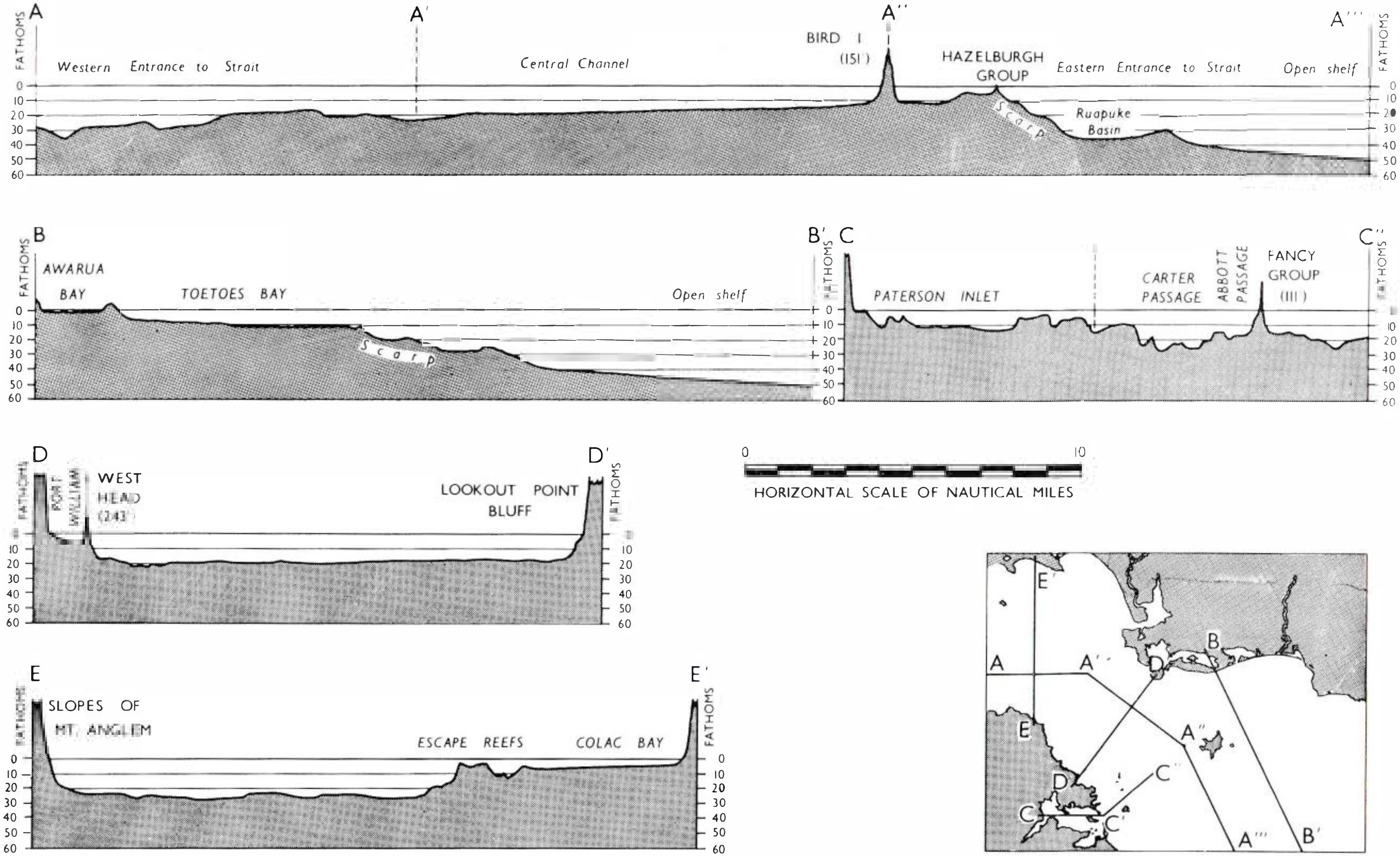


FIG. 3 Bathymetric profiles across Foveaux Strait, constructed from closely-spaced echo-sounding data, obtained from HMNZS *Lachlan* and provided as "collector" sheets by the Hydrographic Branch.

of islands and islets (including Bench I., the Mutton Bird Is, and the Hazelburgh Group) emerges along a line extending north-eastward from the vicinity of Paterson Inlet to Ruapuke I. (fig. 3C). The shoals in the vicinity of Dog I. are probably analogous to Vaughan Cornish's (1898) 'banner banks' in that they have been deposited by weakened currents in the lee of Bluff Peninsula.

Immediately to the east of the island chain, the floor of the Strait slopes down abruptly to a depth of 35 fm, forming a well-defined submarine scarp (fig. 3A) with gradients up to and sometimes exceeding 1:100. Although this feature becomes less pronounced to the north of Ruapuke I., and the gradient in Toetoes Bay is also uniform and gentle, an abrupt change in slope at depths of 35—40 fm can be traced ENE for several miles parallel to the Otago coast. In the opposite direction, depths of 50 fm extend close inshore along the south-east coast of Stewart Island, so that no break in slope at shallower depths can be positively identified in that region.

South-west of Ruapuke I., the scarp is traversed by a broad, clearly defined submarine valley—here named the Rakiura Gap (fig. 1)—with gently curved axis, directed southward between Motunui I. and the Lachlan Shoals. The location and trend of this submarine valley may be fault controlled. At the foot of the scarp this depression is joined by a narrower, tortuous valley which passes between Bench I. and Anglem Point, and extends north-westwards parallel to the Stewart I. coast as a trough 20–25 fm deep. This last feature is in all probability a continuation of the drowned and silted-up river system that now comprises Paterson Inlet, and indeed both of the submarine valleys described above are regarded as remnants of an ancient sub-aerial drainage pattern that developed during a period of lower sea-level. It is doubtful whether such clearly incised features could originate under present conditions, even when the strong tidal currents that are known to scour parts of the Strait are taken into account. The bottom sediments in the vicinity of the two submarine valleys contain comparatively high proportions of fine and very fine sand and mud, which suggests that the bottom currents over this region are correspondingly weak.

Another feature that is considered to have formed during an earlier period of lower sea-level is the unique, enclosed depression—Ruapuke Basin (fig. 1, fig. 3A)—that extends along the foot of the submarine scarp south of Ruapuke I. and constitutes the eastern threshold of the Strait. This depression, roughly elliptical in plan with a length of 10 miles and a maximum width of 3 miles, attains a depth of 37 fm south of Ruapuke. It is barred from the open shelf by a long, narrow ridge, rising in places 10 fm above the deepest part of the depression, and sloping steeply down to 40 fm along its outer margin before levelling off and becoming continuous with the more gentle slopes of the outer shelf.

No mechanism is known by which this topography could have formed in the modern submarine environment, and Ruapuke Basin is interpreted here as the remnant of an ancient, submerged coastal lagoon, comparable with those that occur at the present day along the northern shore of the Strait between Bluff and Fortrose. Similarly, the enclosing ridge to the east is believed to represent a degraded longshore spit inundated by a recent rise in sea-level. The longshore spits that enclose modern lagoons fringing Toetoes Bay are characterised by steep seaward gradients, with typical concave profiles below the present high-water level. A similar profile can be discerned on the eastern slope of the submerged spit (fig. 1, fig. 3A and B), and by analogy the sea-level at the time of formation of the spit is estimated to have stood approximately 35 fm below the present level. It seems not unlikely that the drowned river valleys, described earlier, were graded to this same level, which, it is suggested, represents the ancient shoreline immediately prior to the Flandrian transgression. The preservation of such transient features bears testimony to the rapidity of the transgression.

East of Foveaux Strait, the open shelf slopes gradually downward, over an average width of about 30 miles, from a depth of 40 fm to the shelf edge which in this region lies at 75-80 fm. A local, poorly-defined break in slope at depths of 50-60 fm, east and ESE of Ruapuke I., may represent an even earlier submerged shoreline, although in this instance no better diagnostic morphologic features remain.

Some specific bathymetric features of the Strait having been related to fluctuations of sea-level, the broader topographic features are now considered. The evolution of the longitudinal profile through the Strait, with its gentle westward slope and much steeper eastward slope, is thought to have been controlled by the existence of a rock barrier across the eastern entrance of the Strait, now visible as a chain of islands. It is suggested that, during the Flandrian transgression, the marine advance from the east was initially obstructed by this barrier, and that the main inundation progressed from the west, carving the gentle uniform slope that forms the floor over the greater part of the Strait today.

THE SEDIMENTS

As might be expected in such a shallow region of the continental shelf swept by strong tidal currents, Foveaux Strait is floored largely by coarse sediments. Gravels extend over the entire central area, while sands, although patchily distributed in the Strait itself, almost completely mantle the deeper zone along the inner margin of the open shelf to the east. Muddy sediments have a very limited distribution in the Strait, and were in fact encountered at only three stations (B 218, B 230 and B 237).*

Biogenic calcium carbonate is an important constituent in many of the sediments, particularly in the gravels, the carbonate content of which is seldom less than 25% and occasionally exceeds 80%. Most conspicuous among the organic detritus are worn and broken molluscan shells and skeletal remains of bryozoa.

SAMPLING METHODS

During the sampling programme, bottom sediments and rocks were collected at 57 stations, the majority spaced at 5-mile intervals over a N – S, E – W rectangular grid covering the entire central region of Foveaux Strait and its eastern approaches (fig. 1).

Grab samples

At all but five of these stations, samples were obtained with a Hayward orange-peel grab of 2 cu. ft capacity, 500 lb weight, and diameter of approximately 28 in. when fully extended. The grab was modified by the addition of metal plates above the hemispherical bucket to diminish 'washing-out' of the finer fractions of the sediments during recovery.

These samples are regarded as representative of the sediment lying on the floor of the Strait at each of the stations, and as such form the basis of the present study. However, the depth of penetration of sediment by the grab was not uniform and varied according to the nature of the bottom sediments, being the greatest (16–17 in.) in the gravels and very coarse sands but restricted to a few inches in closely-packed fine sand.

Apart from samples of coarse, angular rock debris, recovered from Sta. B 233 and B 260, only five of the grab samples were found to be unsuitable for full mechanical analysis, because of either small size or excessive washing out of fines during recovery. A portion of each grab sample was retained for detailed examination, care being taken to select a representative fraction from the centre of each haul where loss due to washing out of fine sediment was at a minimum.

All obviously living organisms were removed from the samples. Dead shell material, on the other hand, has been included in the sediment analyses since, after the demise of its occupants, it has come directly under the influence of sedimentary transportation, abrasion, solution, etc., and has behaved in effect just as detrital particles. No preservatives were added to the samples so that any small, soft-bodied organisms remaining in the sediment were eliminated by decomposition before the samples were required for analysis.

The quantity of each sample retained depended upon its particle size, Approximately 35 cu. in. of sands and fine gravels, and 60 cu. in. of gravels of intermediate grade were retained in wide-necked, screw top glass jars, while larger volumes of coarse gravels and rock fragments were more conveniently stored in stout plastic bags.

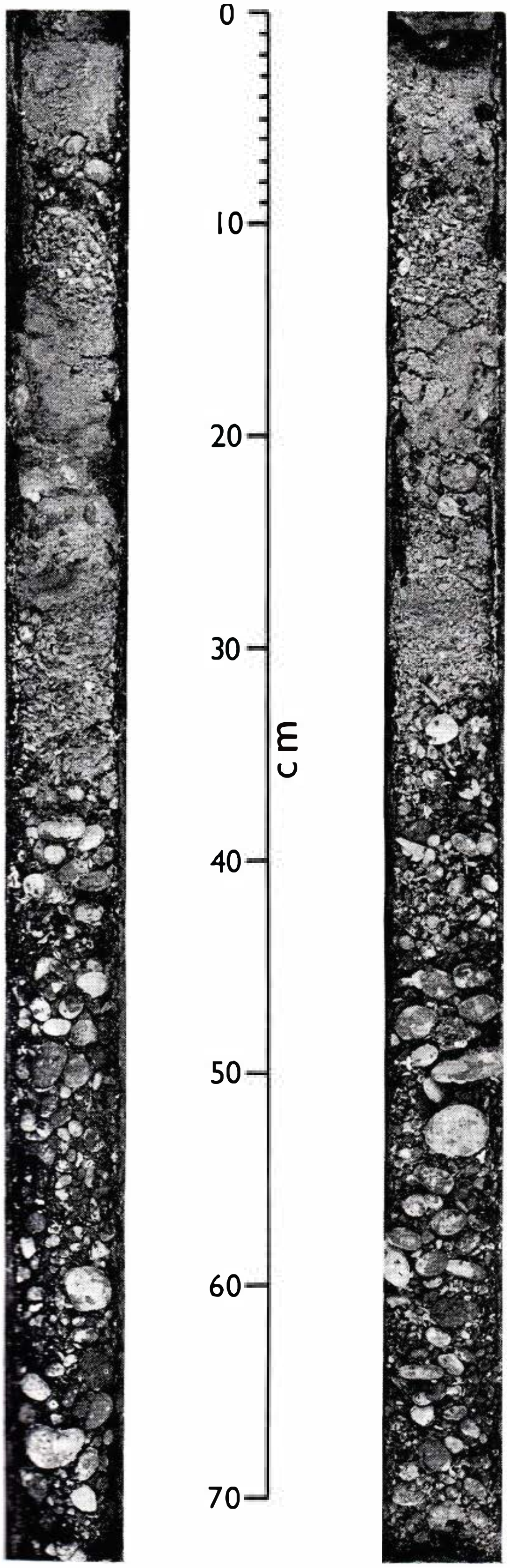
In addition, two small sediment samples (B 283 and B 284) were recovered with a Dietz grab during a traverse across the eastern entrance to the Strait. Although these were sufficient to indicate the general nature of the sediment in the area, they were too small to warrant detailed analysis.

Core samples

Three short cores were recovered from Sta. B 274, B 275 and B 276 in the narrow part of the Strait between Bluff Peninsula and Saddle Point. A 2-in. diameter piston corer was used, with a 12-ft barrel length and driving weight of approximately 450 lb in each case. The trip mechanism was operated by a short, $1\frac{1}{2}$-in diameter, plastic-lined pilot corer, designed to sample the superficial layer of sediment and arranged in such a way as to give the piston corer a free fall of approximately 10 ft.

Although at all three stations the pilot corer failed to collect superficial sediment, cores of shelly sand and gravel, ranging in length from 24–41 in., were recovered by the piston corer.

* Station and sample "B . . ." numbers are identical.



These cores show the existence of gradations and layering within the bottom sediments (plate 5), features that are probably of wide occurrence but usually obliterated in samples collected with the Hayward grab.

GRAIN-SIZE ANALYSIS

Method

The Hayward Grab samples were analysed in the laboratory for size-frequency distribution of their constituent particles.

To avoid handling excessively large volumes of the coarse sediments, a number of preliminary test analyses were made upon progressively smaller sub-samples in an attempt to determine the most convenient amount of material that would give a reliable evaluation for each particular sediment. It was found that for the coarsest gravels a sample of 800–1000 gm minimum weight was required to give a reasonably consistent result, whereas about 500 gm of the finer gravels was normally sufficient. From 180–400 gm of sand were used according to the coarseness of the sediment.

Organic remains that had obviously been alive when the sample was collected were removed before analysis. A special problem, encountered during the textural analyses, was the attachment of encrusting and branching forms of bryozoa to many of the pebbles and dead shells in the Foveaux Strait gravels, which effectively increased the median diameters of the host particles. This was very marked with the branching bryozoa, but less so for the encrusting varieties. No special account was taken of the encrusting bryozoa, and they were treated as part of the host pebble. Although some were perfectly fresh, with the delicate chitinous skeletal parts still preserved, the majority showed considerable abrasion and had in fact been worn quite thin, so that this practice seemed justified.

Very thin, red and white algal encrustations (another common organic coating of pebbles in the Strait) were, like the encrusting bryozoa, disregarded during mechanical analysis. On the other hand, a soft, glutinous, creeping ascidian which cemented the surface pebbles and sand grains at Sta. B 236 into a mat-like mass had to be completely removed.

After extracting extraneous organic material, the following analytical method was adopted. Initially, each sample was decanted with warm water to remove residual salt, a necessary procedure since the salt tended to make the sediment

PLATE 5 Longitudinal section of core B 276, showing alternations of sand and gravel overlying thick gravel at the bottom of the core.

Photograph—J. Whalan

'sticky' and encouraged cohesion of fine sand grains. This procedure was possible because of the virtual absence of particles of mud grade.

The sediments were then thoroughly dried at low heat, and after cooling were passed through a set of nine British Standard sieves ranging in mesh size from 0.066 mm (No. 240 sieve) up to 15.88 mm ($\frac{5}{8}$ in). The entire sieving operation was completed by hand to minimize the abrasion of shell detritus by rock pebbles, which occurs with mechanical shakers such as the automatic 'Ro-tap' machine, producing spurious results.

Pebbles and shell detritus larger than 15.88 mm were measured individually and classified according to whether their maximum diameter lay between 16—32 mm or between 32—64 mm. Particles with dimensions exceeding 64 mm were encountered at only one station (B 238), where the sediment contained large barnacle-encrusted valves of *Ostrea lutaria.*

The only difficulties encountered during the grain-size analyses were with two samples (B 218, B 230), which contained abnormally high proportions of mud (11.3% and 13.8% respectively). The mud particles in these sediments had become tightly bound together by a network of organic fibres—presumably the byssus threads of the bivalve mollusc *Ryenella impacta* present in the sample—which had to be teased apart to allow separation of the sediment. Even then, small masses of fibre persistently aggregated in the sieves, and had to be removed before weighing.

Results

The results of the grain-size analyses are presented diagrammatically as histograms (fig. 4). Incorporated in the latter also are data derived from carbonate analyses, which will be discussed later.

The distinction between the extreme types of sediment in Foveaux Strait—well-sorted sands on the one hand, and bimodal or polymodal gravels on the other—is immediately apparent in the histograms. However, closer inspection shows that subdivision into more specific categories is feasible, as follows

- (i) Coarse pebble gravel
- (ii) Medium to fine, sandy pebble gravel
- (iii) Well-sorted fine to medium sand
- (iv) Muddy sand
- (v) Poorly-sorted shelly sand

In general, the gravels are confined to the shallow central part of the Strait in depths less than 25 fm, while the sands occur mostly as a continuous mantle over the inner margin of the open shelf east of the Strait, at depths greater than 25 fm.

(i) *The coarse pebble gravels* are composed predominantly of pebbles with dimensions exceeding 16 mm. Smaller pebbles also occur, but particles larger than 64 mm are only rarely encountered. The majority of the pebbles are well-rounded, and their shapes range from spheroidal to discoidal and spindle-shaped, according to their lithological character. Granite pebbles, for example, normally yield high sphericity values, while greywacke and argillite pebbles tend towards prolate and oblate shapes. The overall colour of the gravels is also dependent upon the lithology of individual pebbles. Whereas high proportions of greywacke and argillite pebbles impart a sombre dark green appearance to the gravels, the colours are paler in samples containing appreciable quantities of leucogranite pebbles.

Sand is comparatively sparse in this type of gravel. It frequently amounts to less than 10% by weight in individual samples, and seldom exceeds 20%.

Only the largest pebbles are encrusted by bryozoa, movement of the smaller pebbles (probably mere jostling together rather than actual lateral transportation) being sufficient to inhibit the growth of organisms.

The coarse pebble gravels are concentrated in two regions. They floor the entire north-western part of the Strait, where they extend offshore from Oreti Beach westward beyond Centre I. (fig. 5). Further areas of these gravels occur across the eastern entrance to the Strait, in Toetoes Bay, around Ruapuke I. and in the vicinity of Motunui and the Fancy Group. An anomalous occurrence of coarse pebble gravel was encountered at a depth of approximately 40 fm at Station B 267, on the inner margin of the open shelf east of the Strait.

(ii) *Medium to fine, sandy pebble gravel* is the dominant sediment type in the central part of the Strait. It occupies a broad belt that extends eastward from the northern tip of Stewart Island to cover the greater part of the region between Motunui I. and Bluff promontory, finally tapering away near Waipapa Point (fig. 5).

This type of gravel contains both pebbles and sand grade sediment in significant proportions. Most of the pebbles measure less than 16 mm, while the sand (which normally comprises over 20% of the sediment, and sometimes even exceeds the proportion of pebble) includes both coarse (0.50–2.00 mm) and medium (0.25–0.50 mm) grades (plate 6).

Underwater photographs taken in the region floored by this type of gravel indicate clearly the presence of thin veneers of sand, patchily distributed over a gravel surface (plate 7). Those

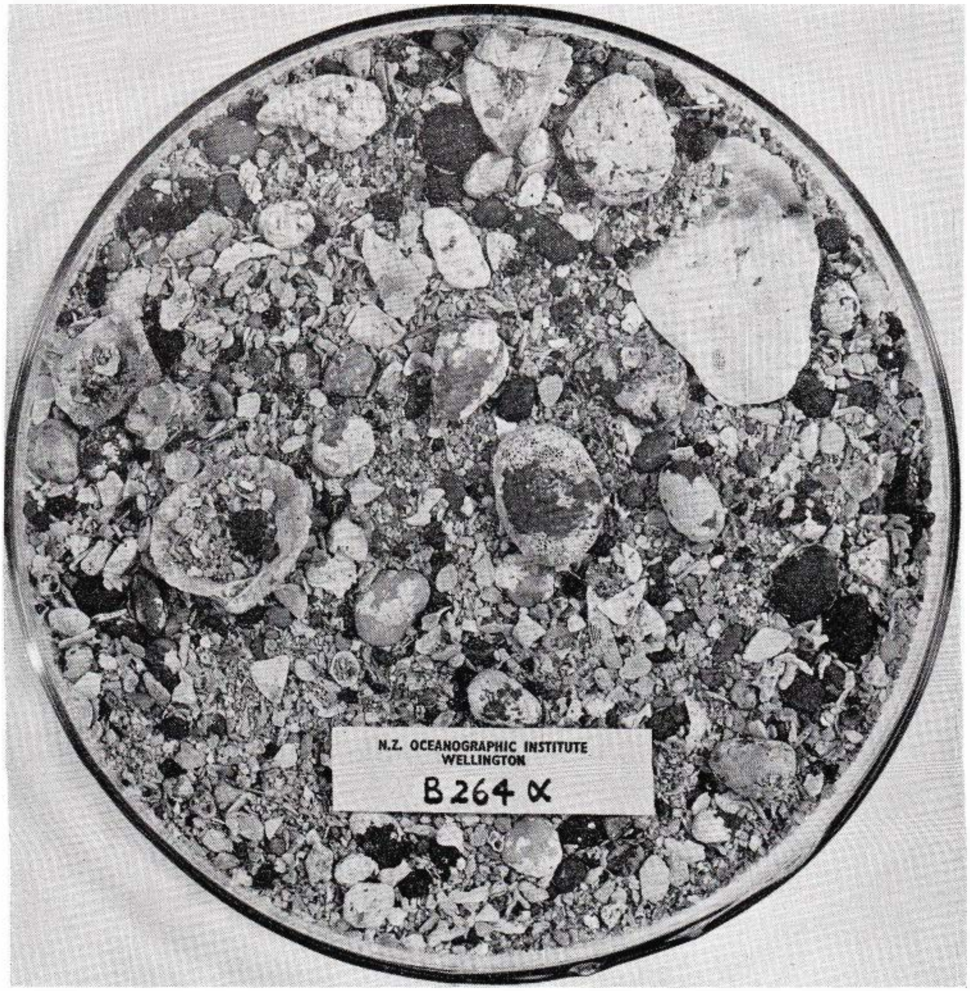


PLATE 6 Detail of medium to fine, sandy pebble gravel (B 264α) showing bryozoa-encrusted pebbles, large mollusc shells, and interstitial coarse shell sand. Approximately $\frac{5}{6}$ natural size.

Photograph—J. Whalan

analyses which show an unusually high proportion of sand, and particularly of medium sand (as at Sta. B 221, B 229 and B 254), reflect the existence of such a sand veneer.

As in the coarse gravel, the pebbles are mostly well-rounded, although a few possess irregular shapes with rough, pitted surfaces.

Fresh, worn and broken shell is an important and very obvious component of both the coarse and the fine fractions in the majority of these gravels, and sometimes (as at Sta. B 264) shell comprises almost the entire 'pebble' fraction. The biogenic debris is composed largely of lamellibranch valves—infaunal species such as *Tawera spissa*, *Glycymeris modesta* and *Venericardia purpurata* being particularly conspicuous—together with gastropod shells, barnacle plates and skeletal fragments of many species of bryozoa.

Bryozoan encrustations on pebbles, many of them quite fresh and unworn, are far more common than in the coarse gravels, and in some samples invest even the smallest of the pebbles. Here it is apparent that the bottom currents, although sufficiently strong to inhibit deposition of the finest grades of sediment, and hence to ensure conditions under which bryozoa can flourish, are not powerful enough to agitate or abrade the pebbles significantly.

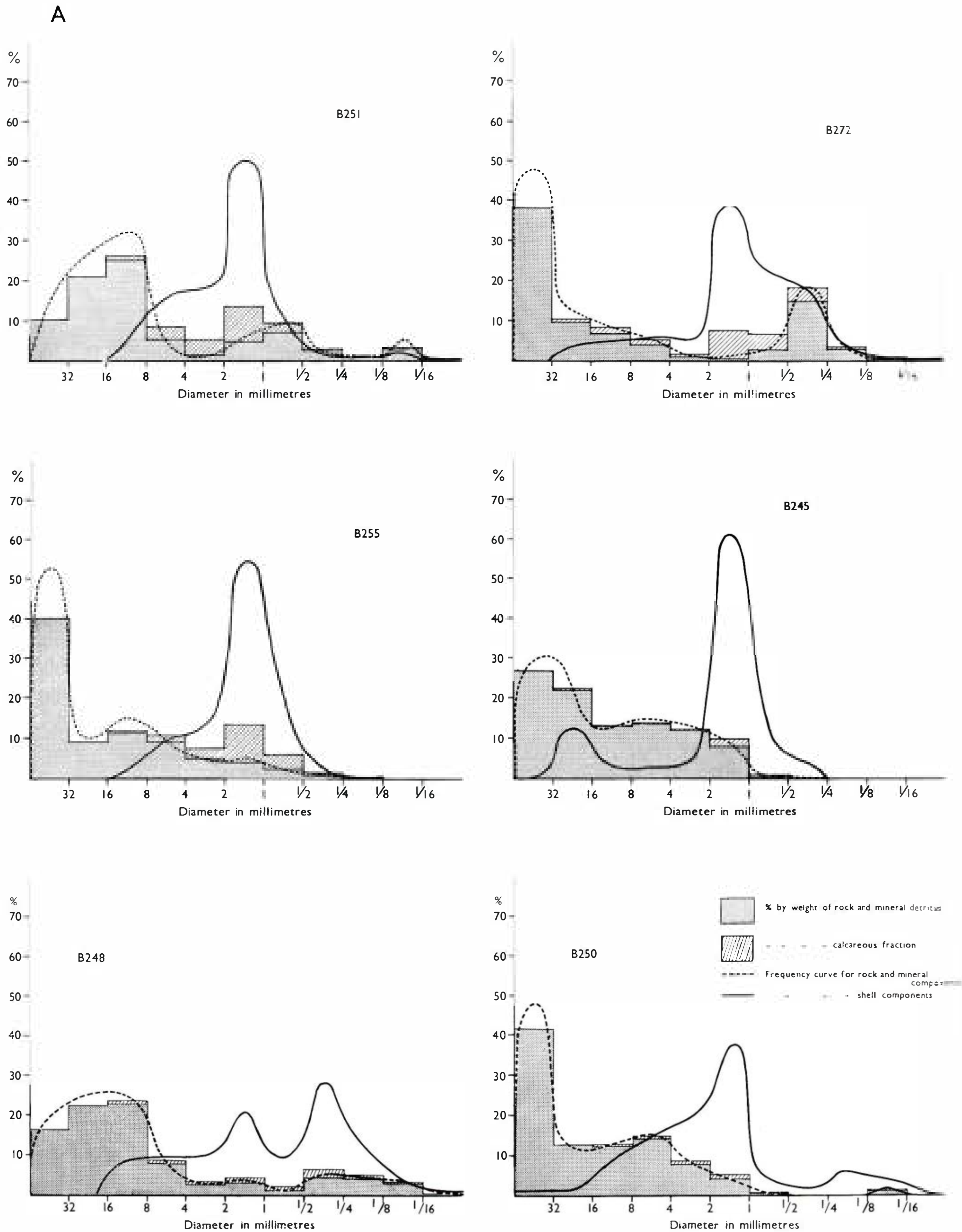


FIG. 4A Combined histograms and frequency curves, showing particle-size distributions in sediments from Foveaux Strait. Coarse pebble gravels: B 251, 272, 255, 245, 248, 250.

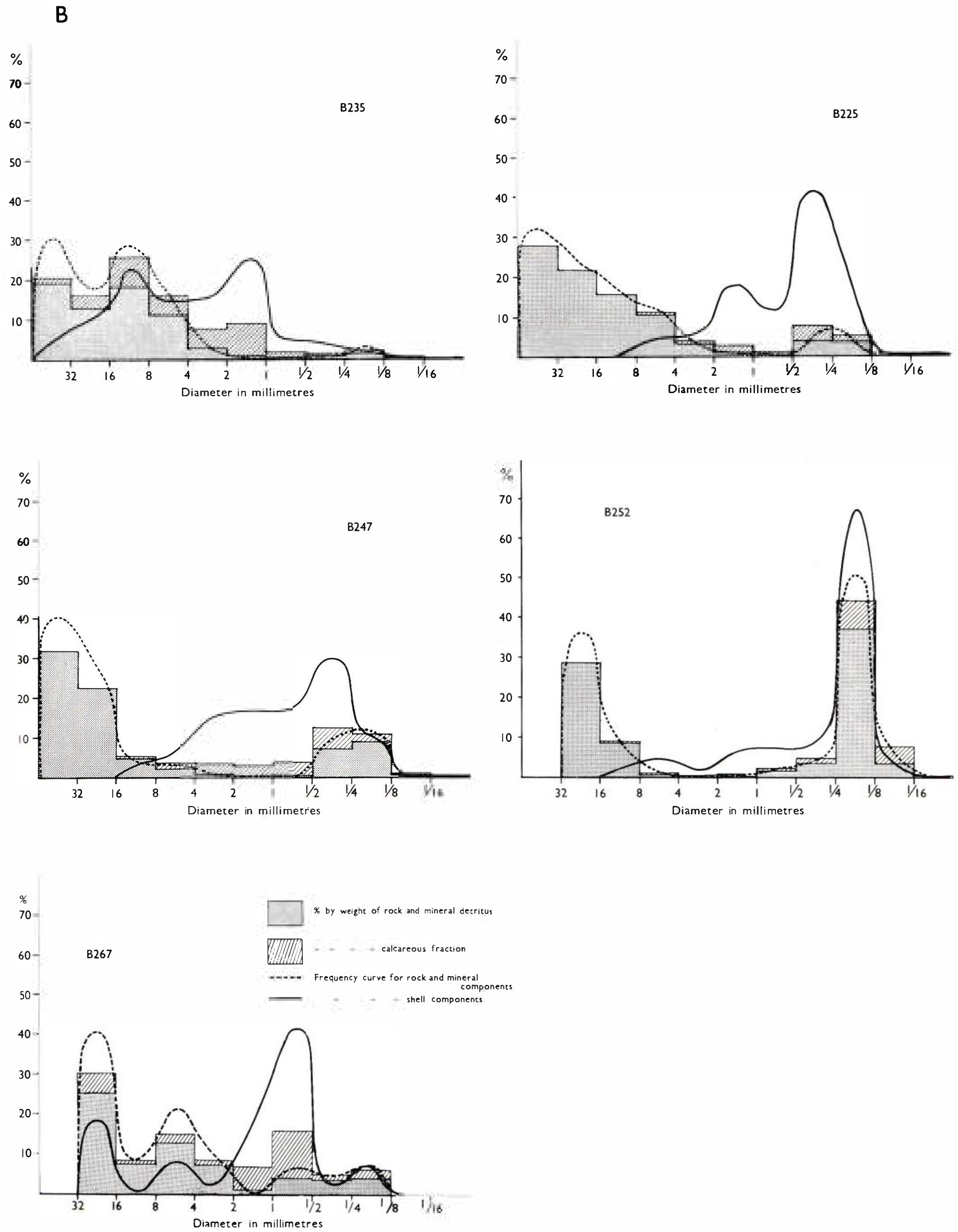


FIG. 4B Coarse pebble gravels: B 235, 225, 247, 252, 267.

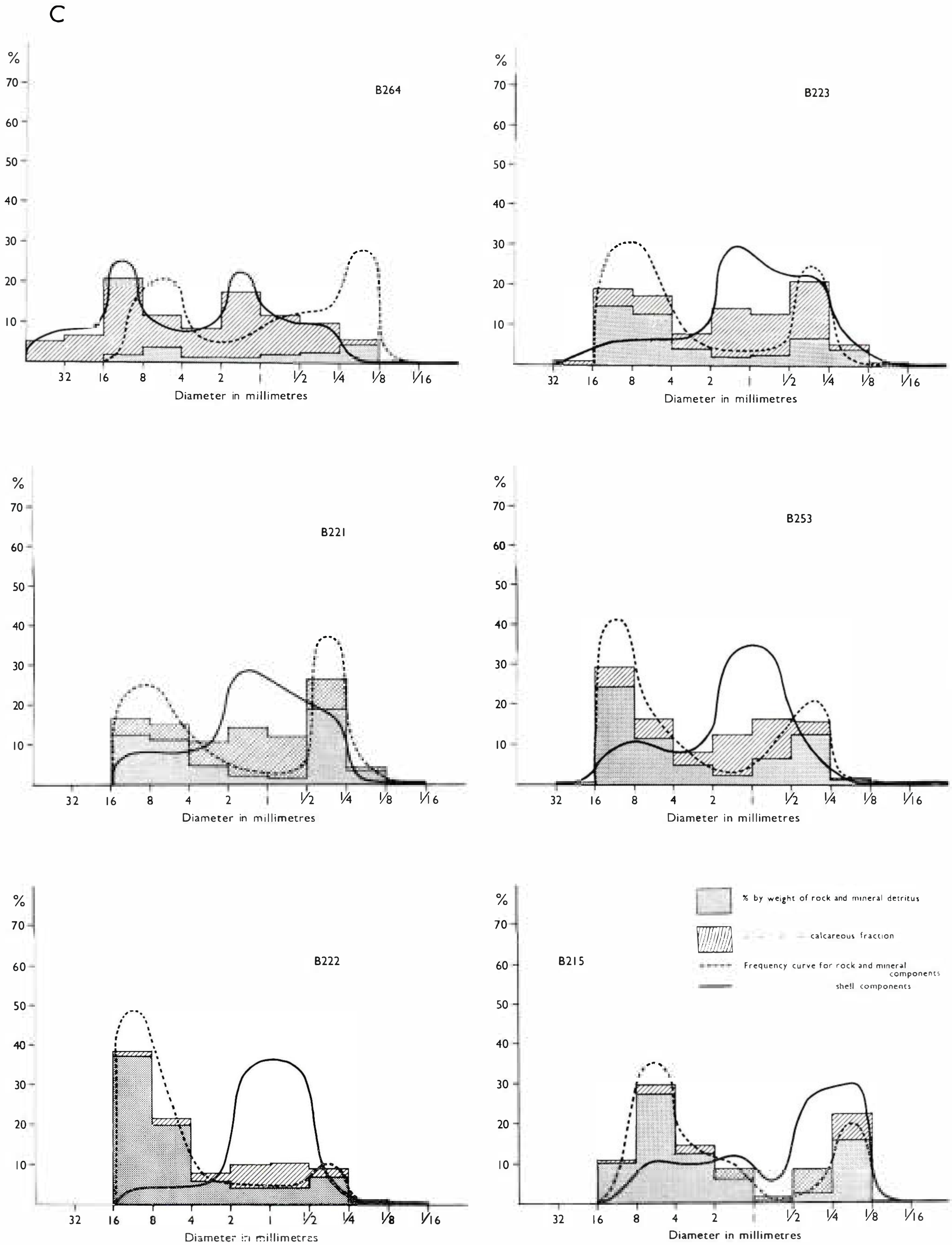


FIG. 4C Combined histograms and frequency curves, showing particle-size distributions in sediments from Foveaux Strait. Medium to fine, sandy pebble gravels: B 264, 223, 221, 253, 222, 215.

D

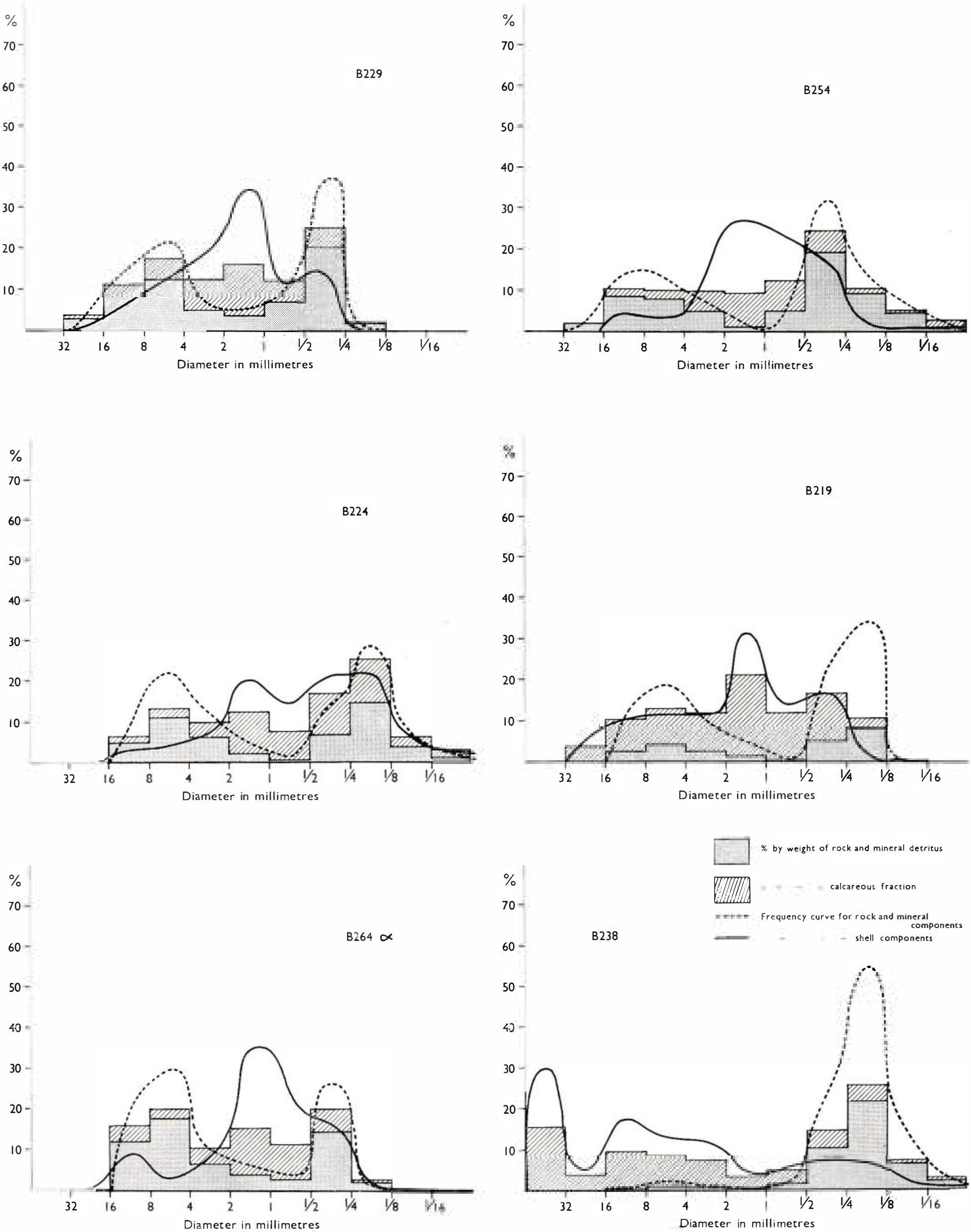


FIG. 4D Medium to fine, sandy pebble gravels: B 229, 254, 224, 219, 264α, 238.

E

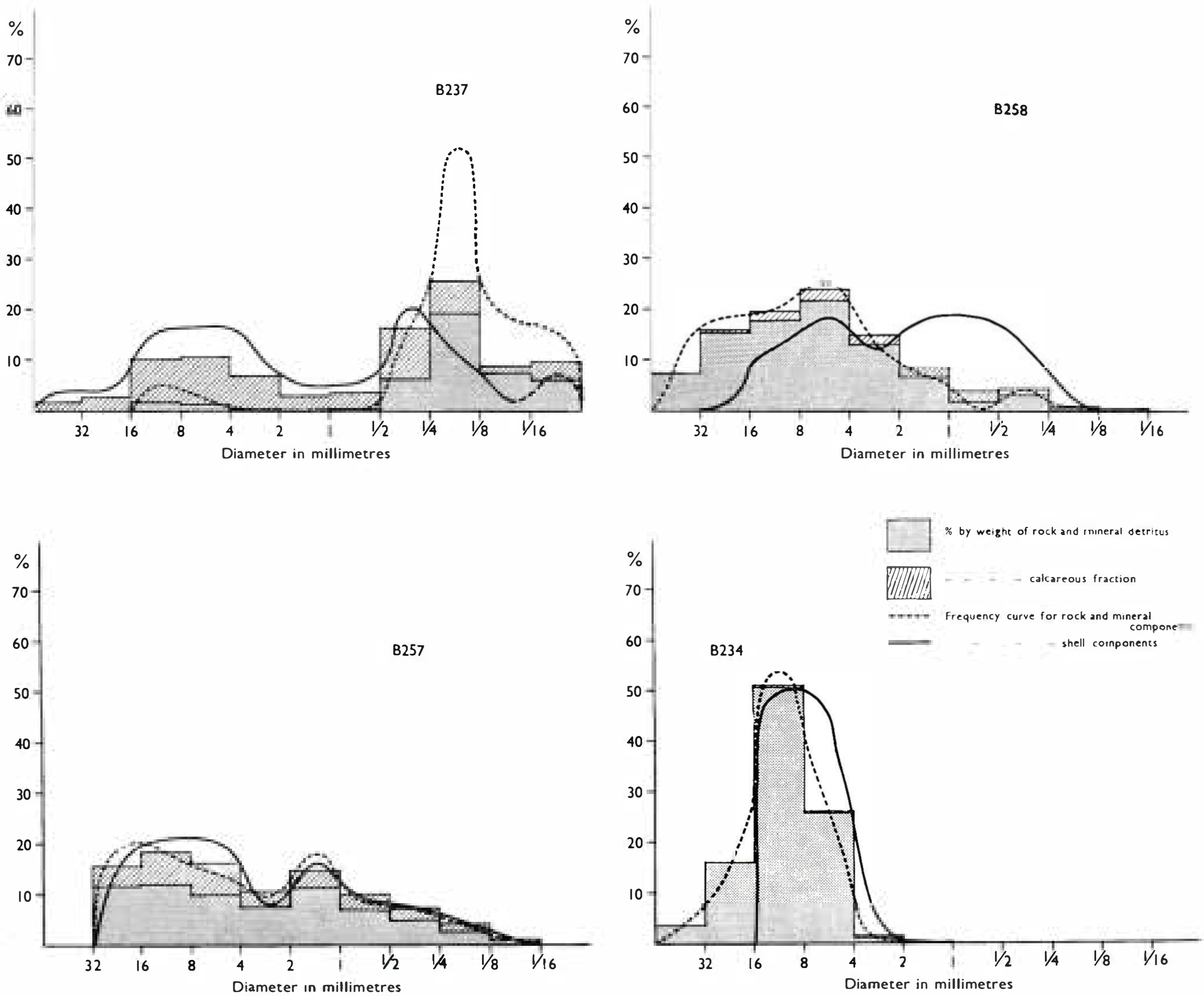


FIG. 4E Combined histograms and frequency curves, showing particle-size distributions in sediments from Foveaux Strait. Medium to fine, sandy pebble gravels: B 237, 258, 257, 234.

F

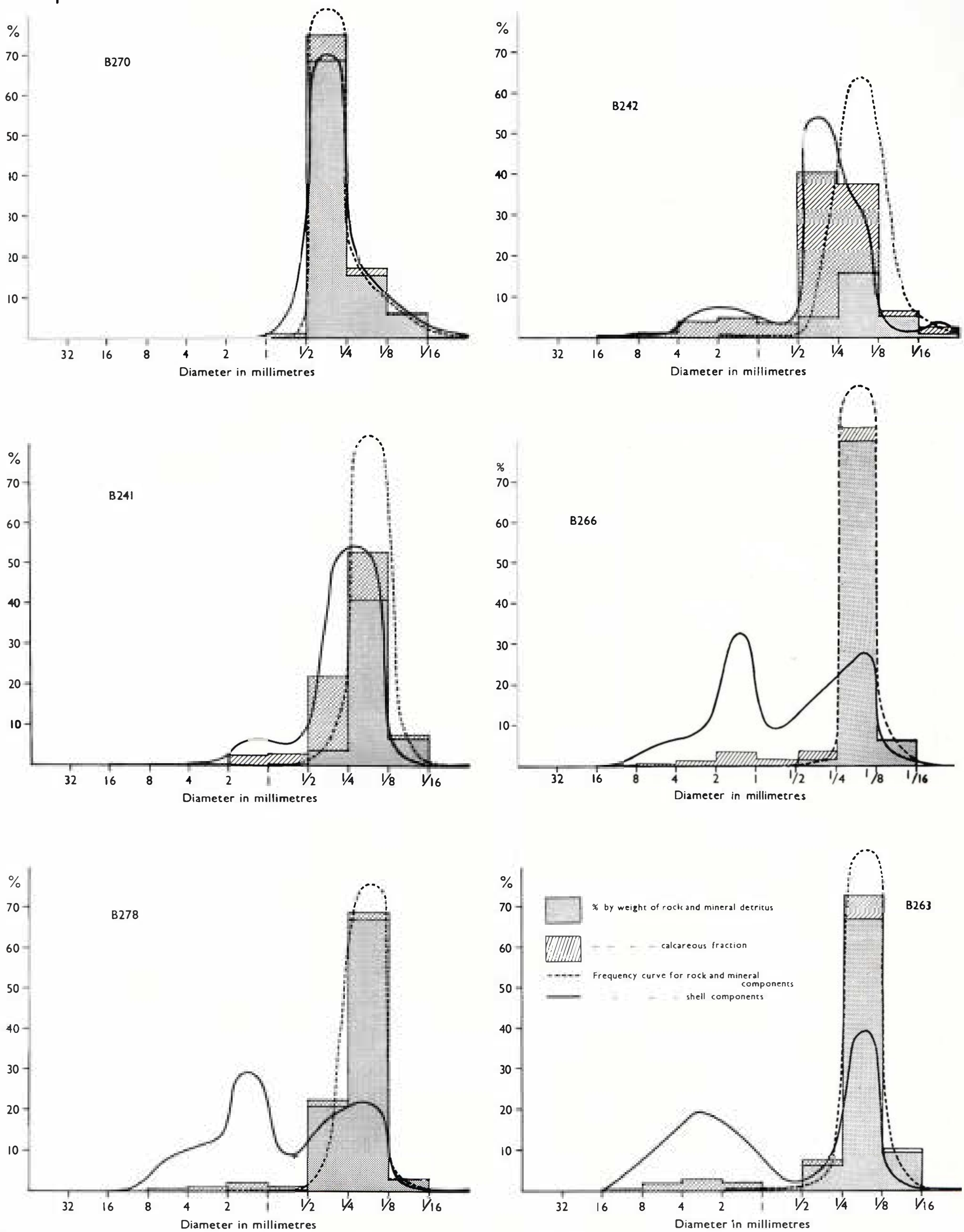


FIG. 4F Medium to fine, well-sorted sands: B 270, 242, 241, 266, 278, 263.

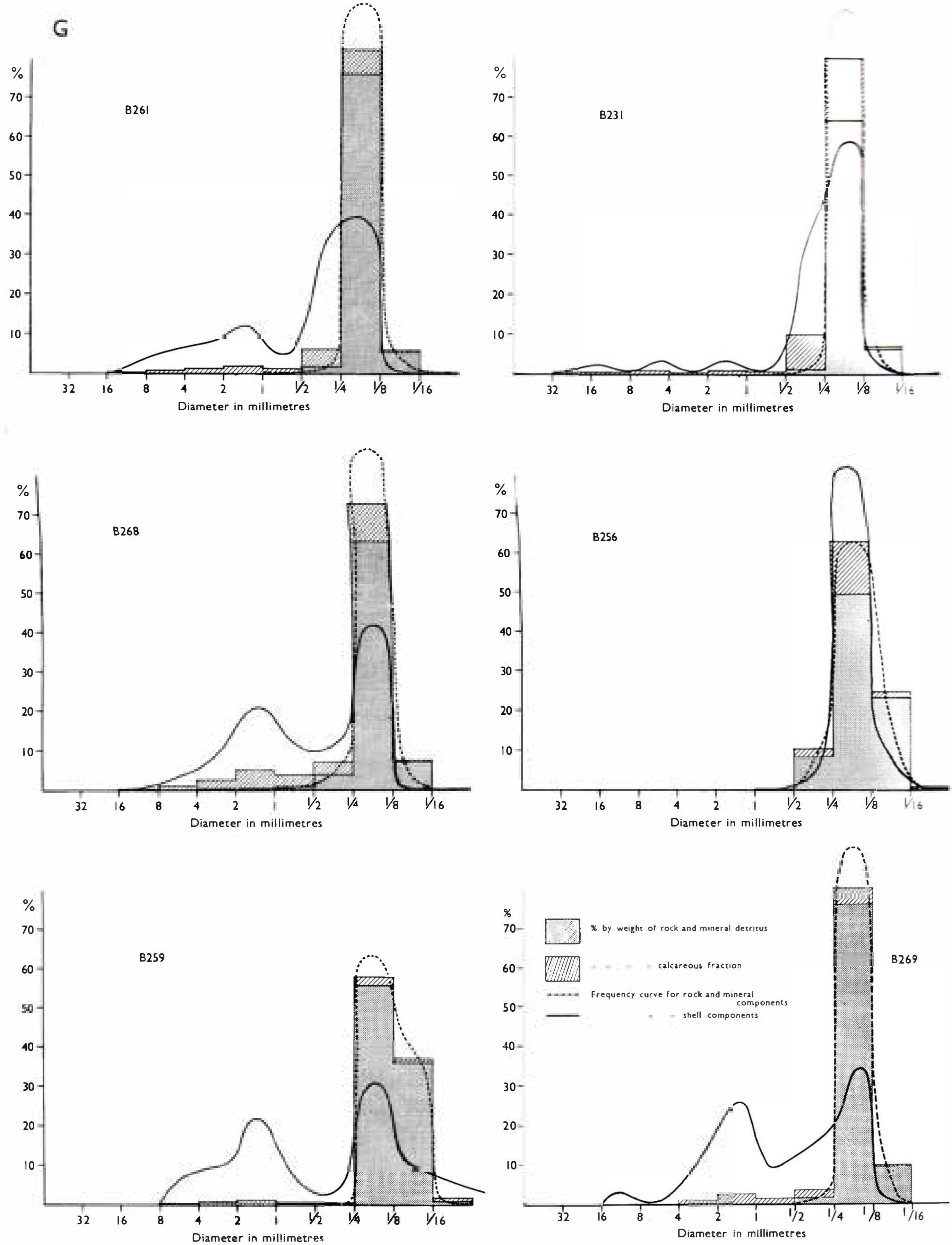


FIG. 4G Combined histograms and frequency curves, showing particle-size distributions in sediments from Foveaux Strait. Medium to fine, well-sorted sands: B 261, 231, 268, 256, 259, 269.

H

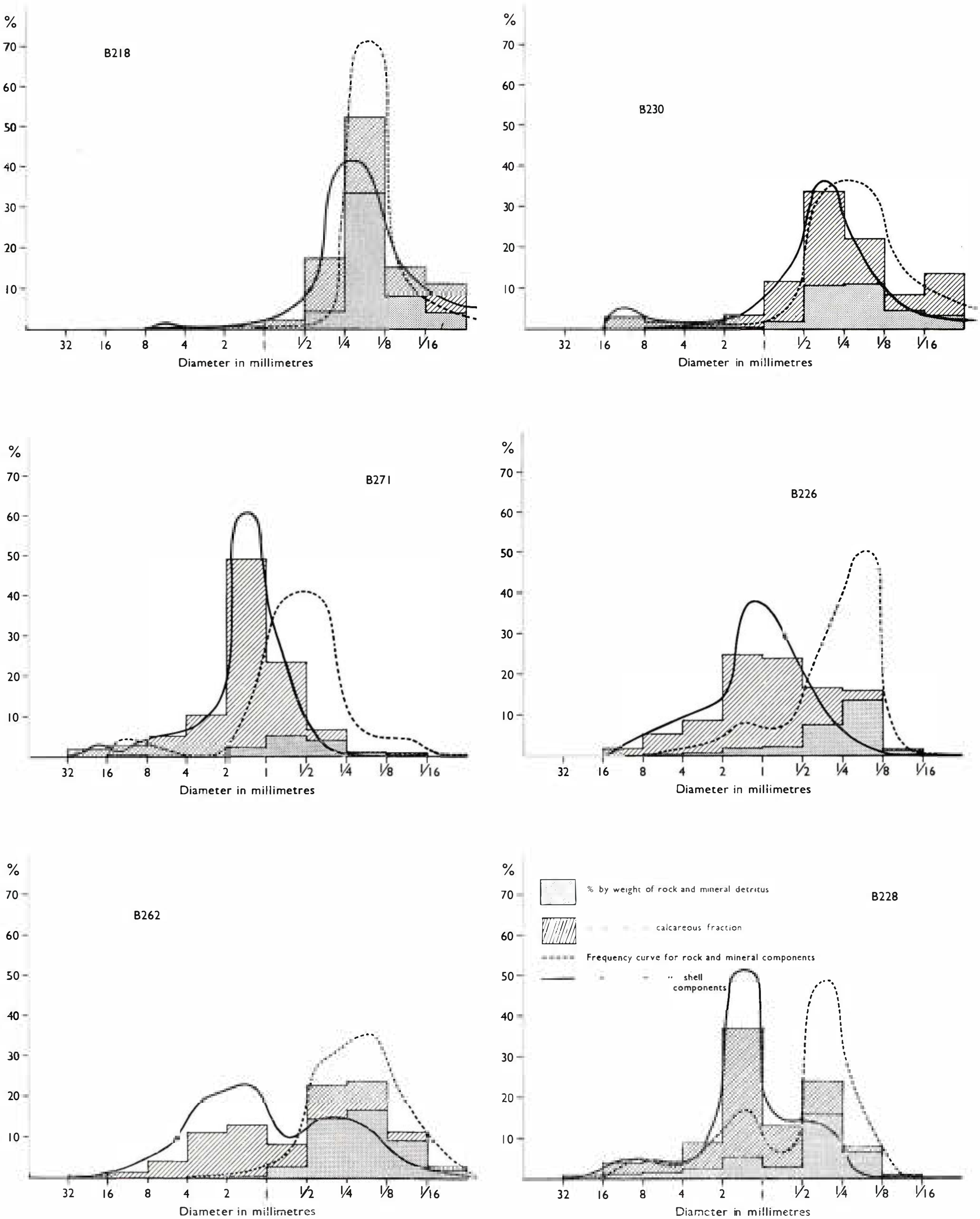


FIG. 4H Muddy sands: B 218, 230. Poorly-sorted shelly sands: B 271, 226, 262, 228.

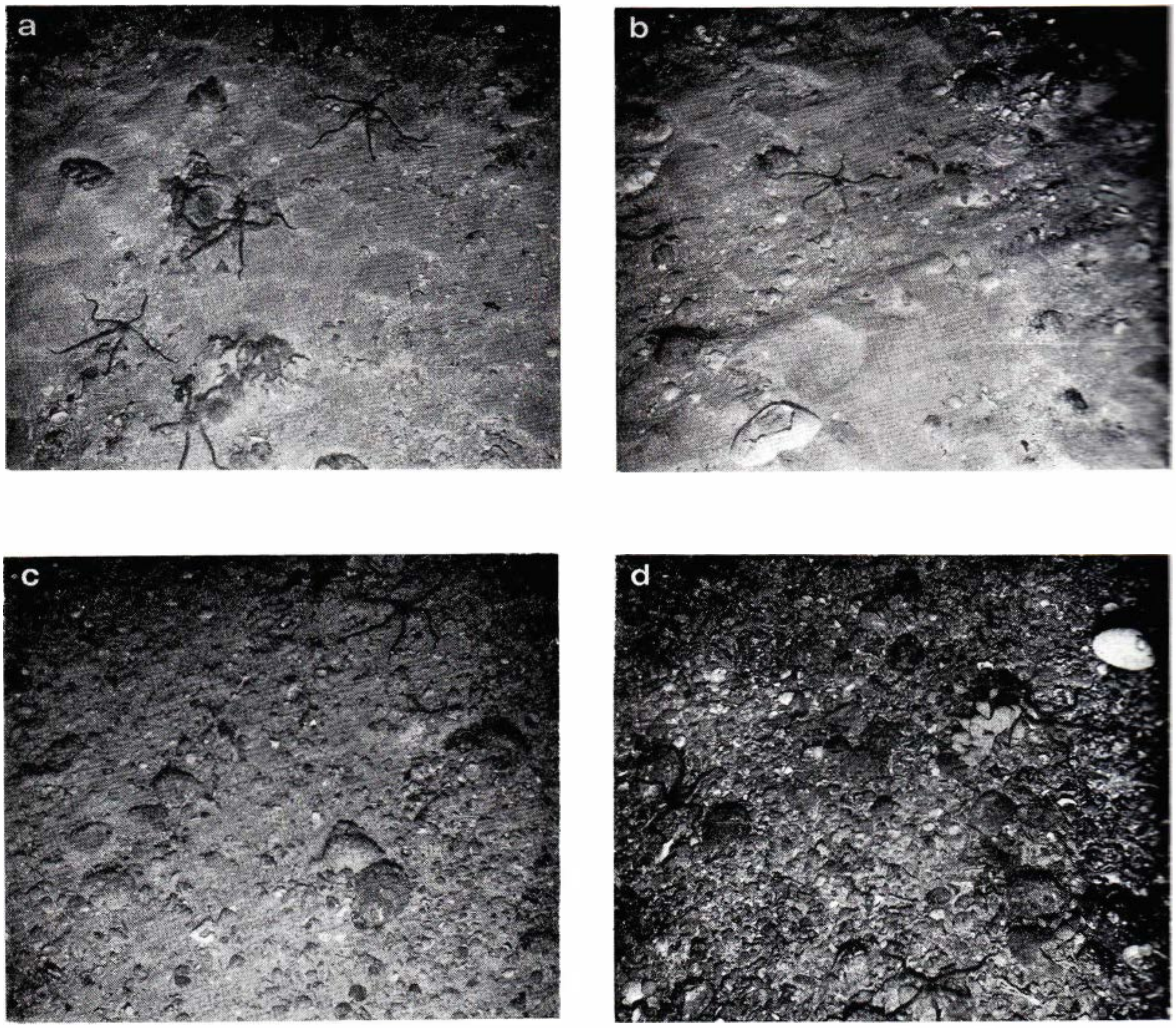


PLATE 7 Sequence of underwater photographs taken as the ship drifted at Sta. B 352. This shows a transition from bottom covered with a veneer of sand to completely gravelly bottom. Distance across sea floor at base of each photograph approximately 75 cm. The ophiuroid is *Pectinura maculata* (Verrill)

Photograph—H. O'Kane

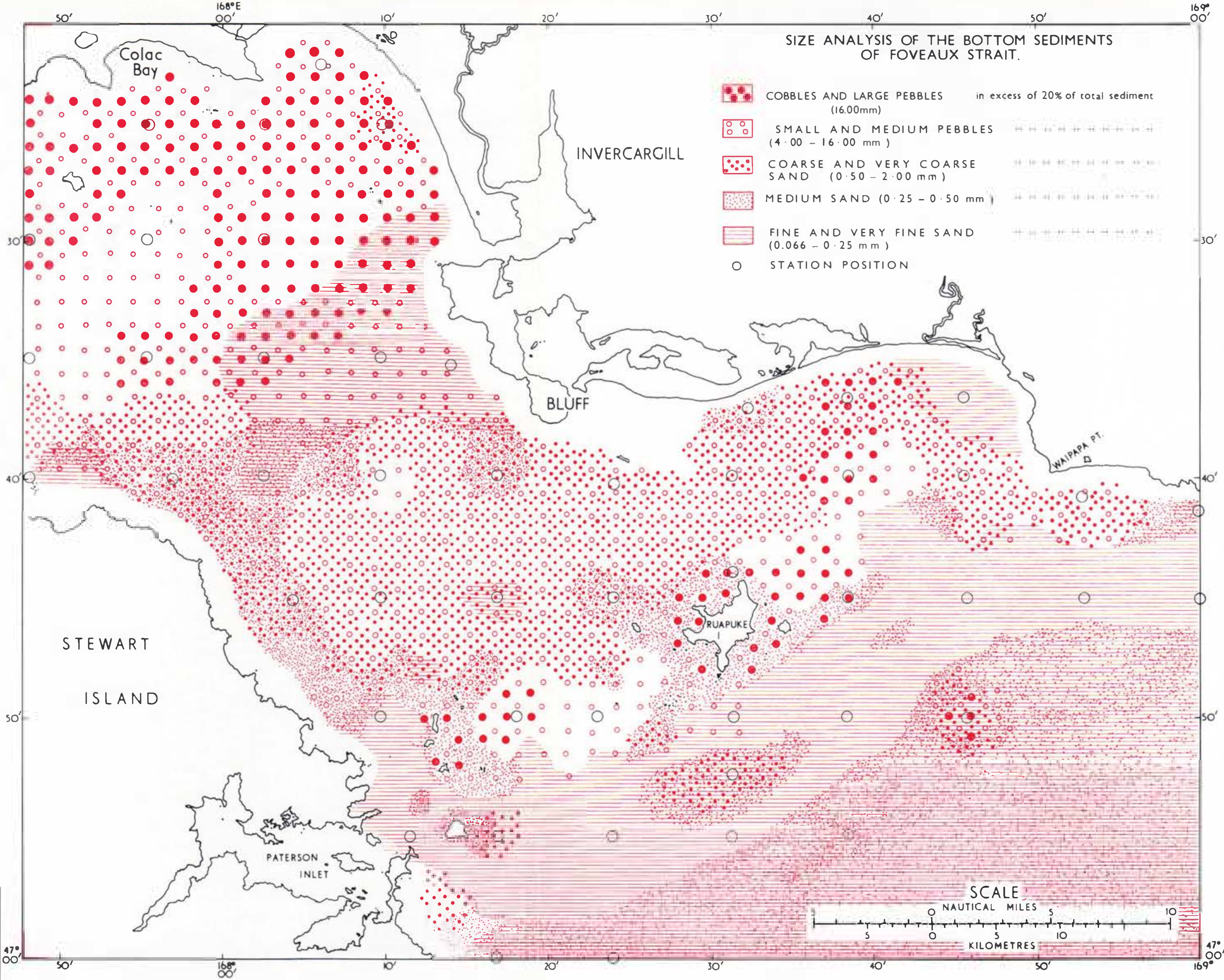


FIG. 5 Areal distributions of particle-size groups in the bottom sediments of Foveaux Strait.

(iii) *Well-sorted fine to medium sands.* Well-sorted fine sand (0.125–0.25mm) is restricted to a narrow continuous belt extending across the eastern threshold of Foveaux Strait, from the entrance to Paterson Inlet to the vicinity of Waipapa Point (fig. 5). The sand lies generally between 20–35 fm on the lower slopes and along the foot of the submarine scarp east of Ruapuke, and more or less parallel to the submerged 35-fm shoreline. Ruapuke Basin, the submerged lagoon south of Ruapuke, although itself floored by a different type of sediment, is completely enclosed within this belt of fine, well-sorted sand.

The sands vary in colour from pale, greyish-brown to medium grey, the darker tints reflecting relatively high proportions of dark-coloured heavy minerals, of which magnetite and dark mica are the most common. Small amounts of coarse biogenic detritus are often present, and consist of shells of the small gastropod *Stiracolpus symmetricus* and skeletal remains of a very characteristic plano-convex, free-growing bryozoan, *Selenaria* (plate 8).

Fine sands occur also off the mouths of some of the more mature rivers that discharge into the Strait. The sand flooring the eastern end of Toetoes Bay, for instance, has quite clearly been carried into the Strait and deposited by waters from the Mataura River (figs. 5, 6), although its preservation here is probably due, partly at least, to the local shape of the coastline.

Included in the same sediment class are slightly coarser sands which contain particles of both fine (0.125-0.25 mm) and medium (0.25-0.50 mm) sand grade, sometimes in roughly equal proportions as in sample B 242. Here the shape of the histogram is misleading, as the sediment is just as well sorted as the fine sands. The median

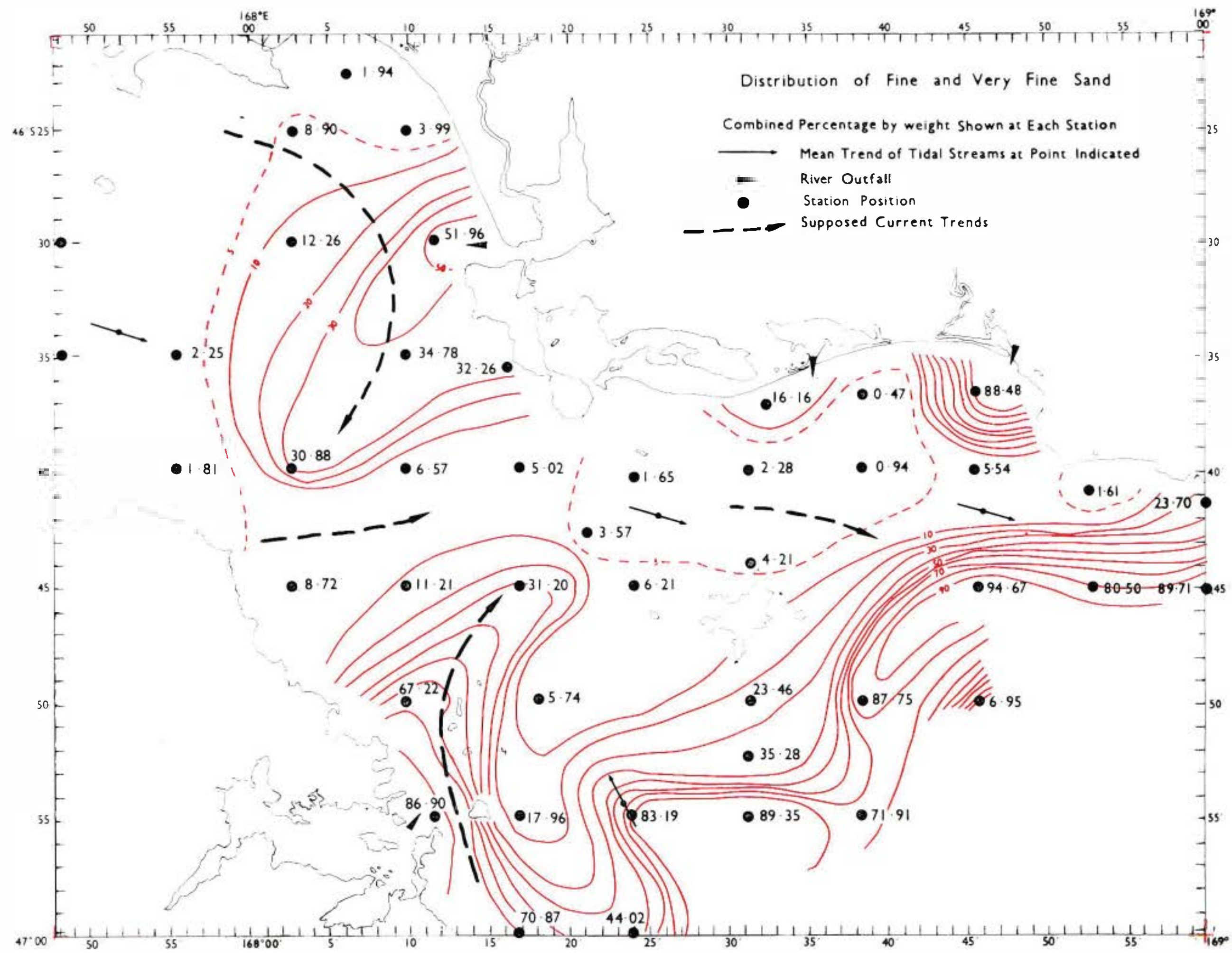


FIG. 6 Distribution of fine and very fine sand in Foveaux Strait. Isopleths based on percentages by weight of total sediment, and drawn at 10% intervals.

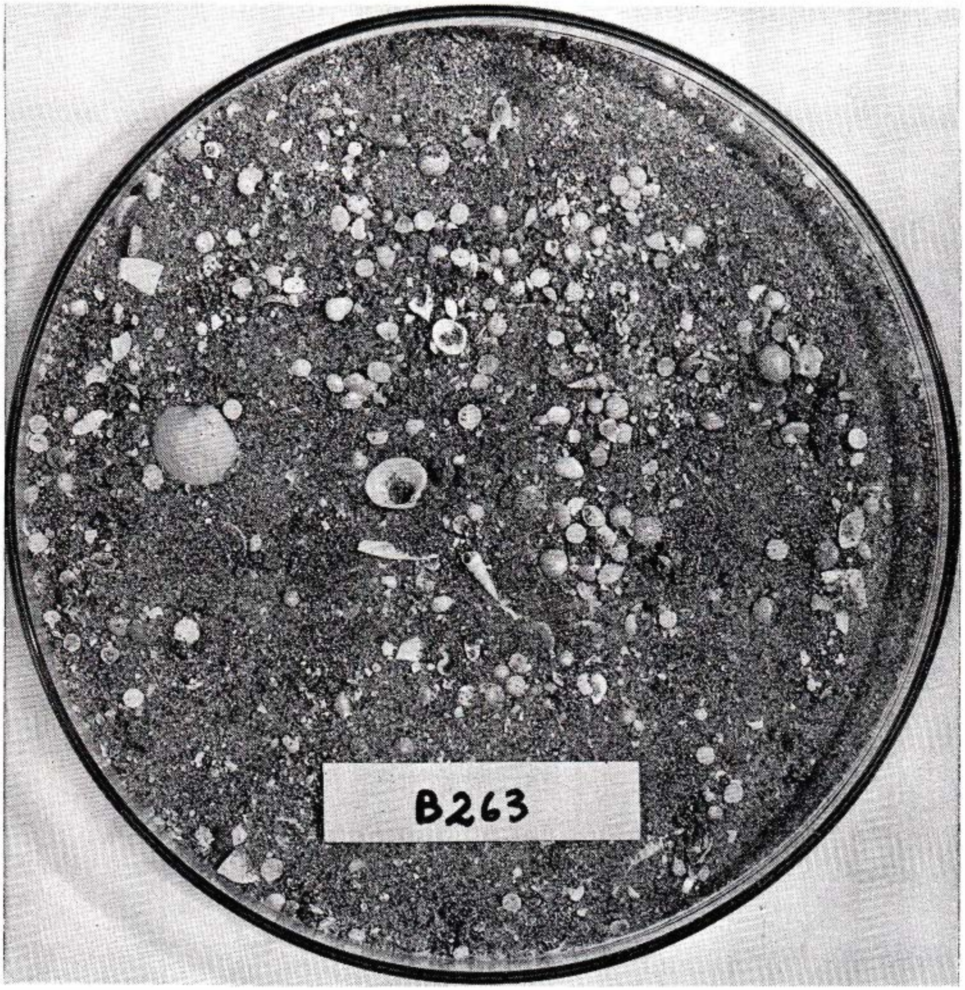


PLATE 8 Detail of well-sorted fine sand from Sta. B 263 showing the characteristic "bun"-shaped bryozoan, *Selenaria*, and shells of the gastropod, *Stiracolpus*. Approximately $\frac{5}{6}$ natural size.

Photograph—J. Whalan

diameter of sand in B 242, however, coincides with the arbitrary division (0.25 mm) between fine and medium sand, so that the sediment contains particles from both categories.

In all other respects, these slightly coarser sands are indistinguishable from the well-sorted fine sands. Samples (B 241, B 242) collected from the area east of Cape Edwardson, however, are exceptionally pale-coloured because of admixture of considerable quantities of shell detritus.

The sands of coarser type are widely distributed over the gently sloping open shelf east of the Strait, in depths ranging from 35 fm downward to the limit of sampling at approximately 50 fm.

(iv) *Muddy sand.* Also regarded as having been transported into the Strait by present-day rivers are the fine sands, usually mixed with small amounts of mud. The distribution of muddy sand in sediments around the estuary of the Oreti River suggests very strongly a fluviatile provenance, the extension of this type of sediment south-westward across the Strait to within a few miles of Saddle Point reflecting the local pattern of water circulation (fig. 7). Similarly, the tongue of sediments, rich in muddy sand, that extends north from the entrance of Paterson Inlet, presumably results from the dispersal by marine currents of fine detritus entering the Strait from the Inlet. The muddy sand that appears in the sediments close inshore at the western end of Toetoes Bay is presumably an accumulation of fine material discharged from the Waituna Lagoon.

There can be little doubt that the fine sand and mud in samples from these areas represent, in part at least, a thin and probably transient

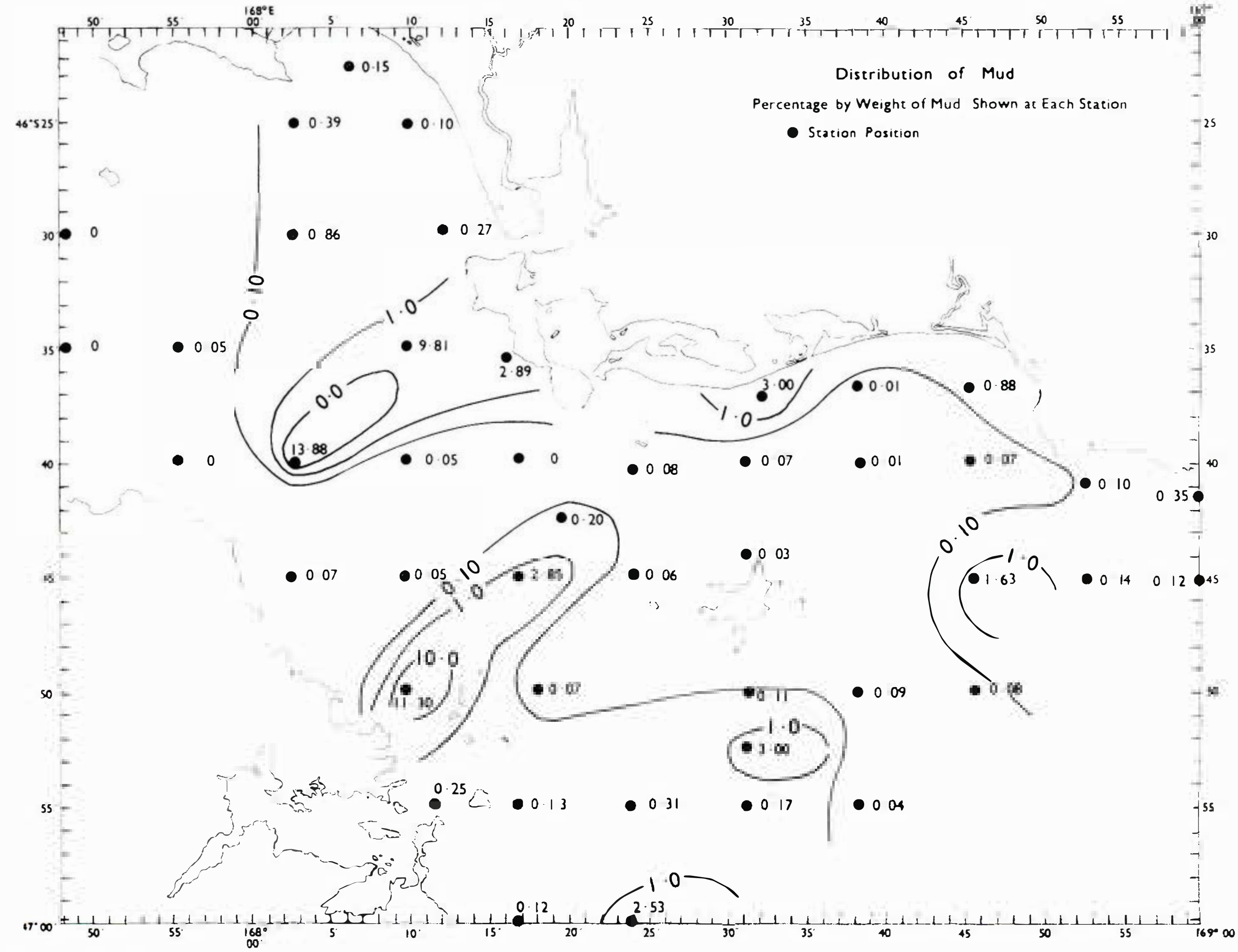


FIG. 7 Distribution of mud in Foveaux Strait. Isopleths based on percentages by weight of total sediment, and drawn at 10% intervals.

veneer upon the surface of the ubiquitous gravel, although evidence of any stratification that may originally have existed has not been preserved by the sampling method. Some intermingling of the sand and mud with subjacent gravel may have occurred *in situ* as a result of downward percolation of the fine sediment.

The proportions of fine and very fine sand in samples from the regions just specified vary from 10% to over 50% by weight, while the mud content is also unusually high, reaching 9.8% at Sta. B 237 and 13.9% (the highest value in the entire Strait) at B 230. The last two figures are in marked contrast with the normal proportions of mud in the Foveaux Strait sediments (generally below 0.1% and only occasionally exceeding 1.0%).

Preservation of the layer of muddy sand in a region swept by powerful bottom currents can be explained partly by cohesion of the sediment, and partly by its entanglement among the byssus threads of bivalve molluscs such as *Ryenella.*

(f) *Poorly-sorted shelly sand.* This sediment is composed essentially of a mixture of very coarse, coarse, medium and fine sand, more or less in equal proportions. Sediments of this type are not common in the Strait, and have been encountered at only three stations.

The floor of the submerged lagoon south of Ruapuke I. is mantled by a sediment that is representative of the poorly-sorted sands. In sample B 262, very fine, fine and medium sand together form the dominant part (approximately 55%) of the sediment, the remainder comprising an appreciable quantity of shell detritus of very

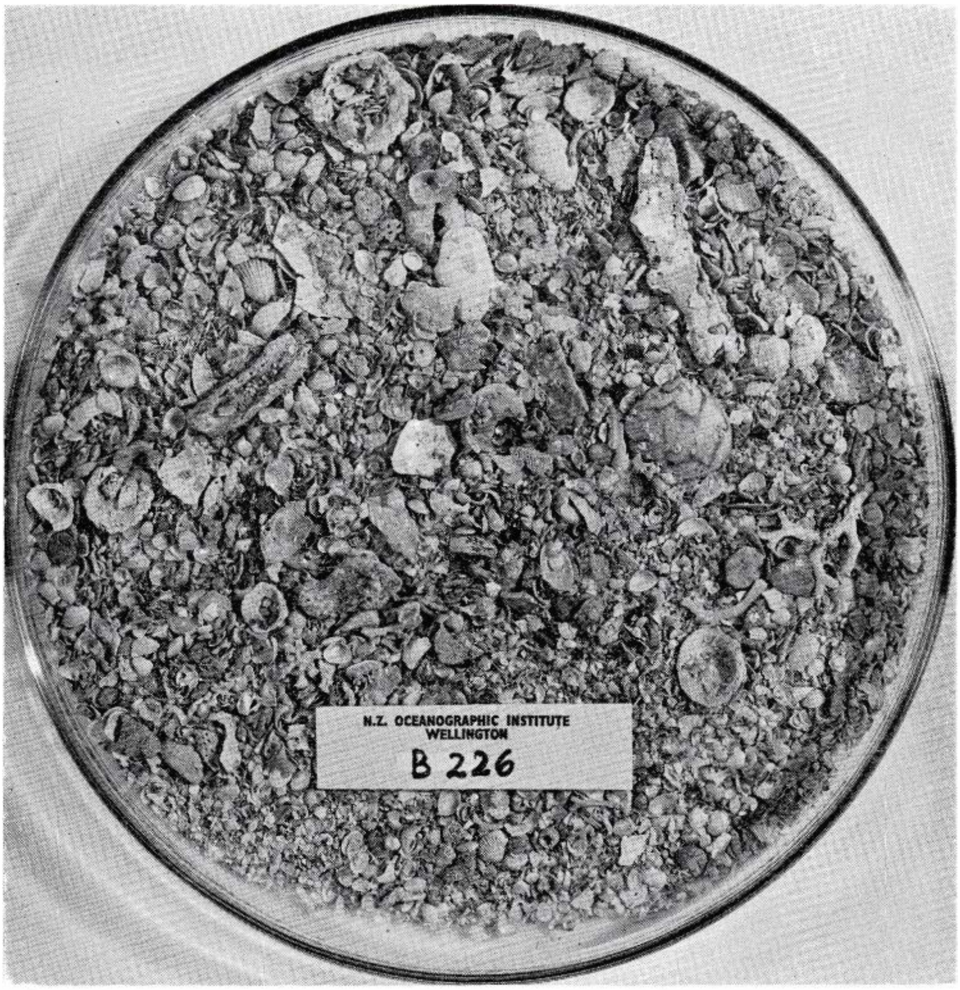


PLATE 9 Detail of poorly-sorted shelly sand from Sta. B 226, showing whole and fragmental molluscan shell, barnacle plates and bryozoan zoaria. Approximately $\frac{5}{6}$ natural size.

coarse sand and granule grade (1.0–4.0 mm), and a small but significant amount (3%) of mud. Almost all of the coarse biogenic fraction is formed of brown-stained *Selenaria* zoaria and broken lamellibranch valves.

Sample B 226 is very similar (plate 9), but B 228, although included in this sediment category, is somewhat atypical in that it displays a bimodal grain-size frequency distribution with maxima in the very coarse and medium sand grades. B 228 is regarded as transitional to the unusual sediment recovered at B 271, which is a moderately-sorted very coarse shelly sand. As abundant shell detritus in the very coarse and coarse sand grades is one of the characteristics of the poorly-sorted shelly sands, B 271 could be regarded as showing some affinity with this class of sediment.

Since data obtained from carbonate analysis of the samples are incorporated with the histograms in fig. 4, discussion of the implications of the size-frequency distributions is deferred until details of these analyses have been given.

CARBONATE ANALYSIS

Shell debris is an important constituent in the majority of sediments from Foveaux Strait, and in several samples its proportion by weight exceeds that of the combined rock and mineral particles. The amount of carbonate in each sample was determined not only to ascertain the distribution of shell within the sediments, but also to investigate its sedimentological significance.

The biogenic fraction of the sediments in the Strait is composed largely of valves (whole or fragmental) of infaunal and epifaunal species of lamellibranch, together with gastropod shells, barnacle plates and the skeletal remains of many species of bryozoa.

Although a few of the shells are quite fresh, and their external colouring and ornamentation and internal nacreous layer perfectly preserved, the majority are weathered, with white, chalky, porous surfaces, pitted and perforated by boring organisms. In certain parts of the Strait, as at B 262 and B 271, brown ferruginous discoloration of shell detritus is very marked.

Method

Following particle-size analysis, a determination was made of the amount of shell detritus in the individual grades of each sample. In the coarse fractions, the shell was picked by hand or with blunt forceps and weighed to the nearest 0.1 gm on a Mettler torsion balance. Carbonate from the sands and finer sediments (i.e. grades with diameters less than 2.0 mm) was separated by immersing weighed sub-samples of appropriate size in dilute hydrochloric acid in open silica dishes, and allowing the carbonate to dissolve completely. Sub-samples of 7–10 gm were found to be adequate for the coarse and very coarse sand grades; for the medium sand, sub-samples of approximately 4 gm were used; while 2 to 3 gm were ample in the case of the fine sand, very fine sand, silt and mud.

When the shell had dissolved completely and effervescence had ceased, the sub-samples were thoroughly washed by decantation, care being taken to flush away, where practicable, the residual sludge (comprising organic fibres, flocculant iron hydroxide and minute mineral grains that had been trapped in pores in the shell).

Surface tension effects caused some difficulty during the washing of the fine grades of sediment, as the grains tended to float on the surface and spill over with the decanted fluid. To overcome this, the solution was diluted and two drops of liquid detergent (Teepol) added before washing. This lowered the surface tension and allowed all the grains to sink to the bottom of the dish. After repeated washing and decantation of individual samples, the grains once again tended to float to the surface, and at this stage they were presumed to be cleansed of both acid and detergent.

The residual mineral grains were then dried at low heat, allowed to cool, and weighed to the nearest 0.1 mg. The proportions of shell in the individual grades of each sample were then readily computed to an accuracy better than 0.1%.

Results (carbonate distribution)

The dominant feature of the distribution pattern of shell detritus (fig. 8) is the progressive increase in the amount of shell towards the centre of the Strait. The proportions by weight rise from less than 10% on the open shelf to the east and west, to over 50% in the narrow stretch of channel between Bluff promontory and the north coast of Stewart Island. An abnormally high carbonate content (81.9%) characterises sample B 264, and high values occur also in B 219 (74.6%) and B 228 (63.8%). The bulk of the shell in these samples is fragmental, and it seems that the carbonate concentration indicates not only the local occurrence of extensive shell beds, but also the existence of bottom currents capable of disrupting the beds and distributing the shell debris over a wide area.

Concentrations of shell exceeding 75% occur also at B 226 and B 242, respectively east and south-east of the entrance to Paterson Inlet, while the highest carbonate value in the Strait—86.3%—was found at Sta. B 271, close to Waipapa Point. A carbonate content of 53%, also somewhat higher than average, characterises the poorly-sorted sand from B 262 in the centre of Ruapuke Basin, much of the 'shell' here consisting (as already described) of *Selenaria* zoaria.

Also revealed by the carbonate distribution pattern is a marked contrast in shell content between sediments offshore from steep rocky coasts, and those on the gentle bottom slopes near low-lying, prograding coasts. This is particularly noticeable in the northern sector of Foveaux Strait, where patches of shelly sediment off Waipapa Point and Bluff Peninsula alternate with areas of sediment relatively poor in carbonate in Toetoes Bay and off Oreti Beach. The existence of strong bottom currents in the two latter areas is inferred from the coarseness of the local sediments, and the paucity of sand in these sediments may have helped to restrict the development of shell beds (and hence to limit the supply of shell debris) over much of the northern part of the Strait.

The tongue of low-carbonate sediment that stretches north-westward between the Fancy Group and the Lachlan Shoals coincides in location and extent with the Rakiura Gap, a feature already described as a possible drowned river valley. While this association is clear enough, the orientation of this tongue appears to be related to the hydrology of this part of Foveaux Strait, for current measurements published by the Hydrographic Branch (1952) indicate that here the mean surface movement of water is also directed north-westward.

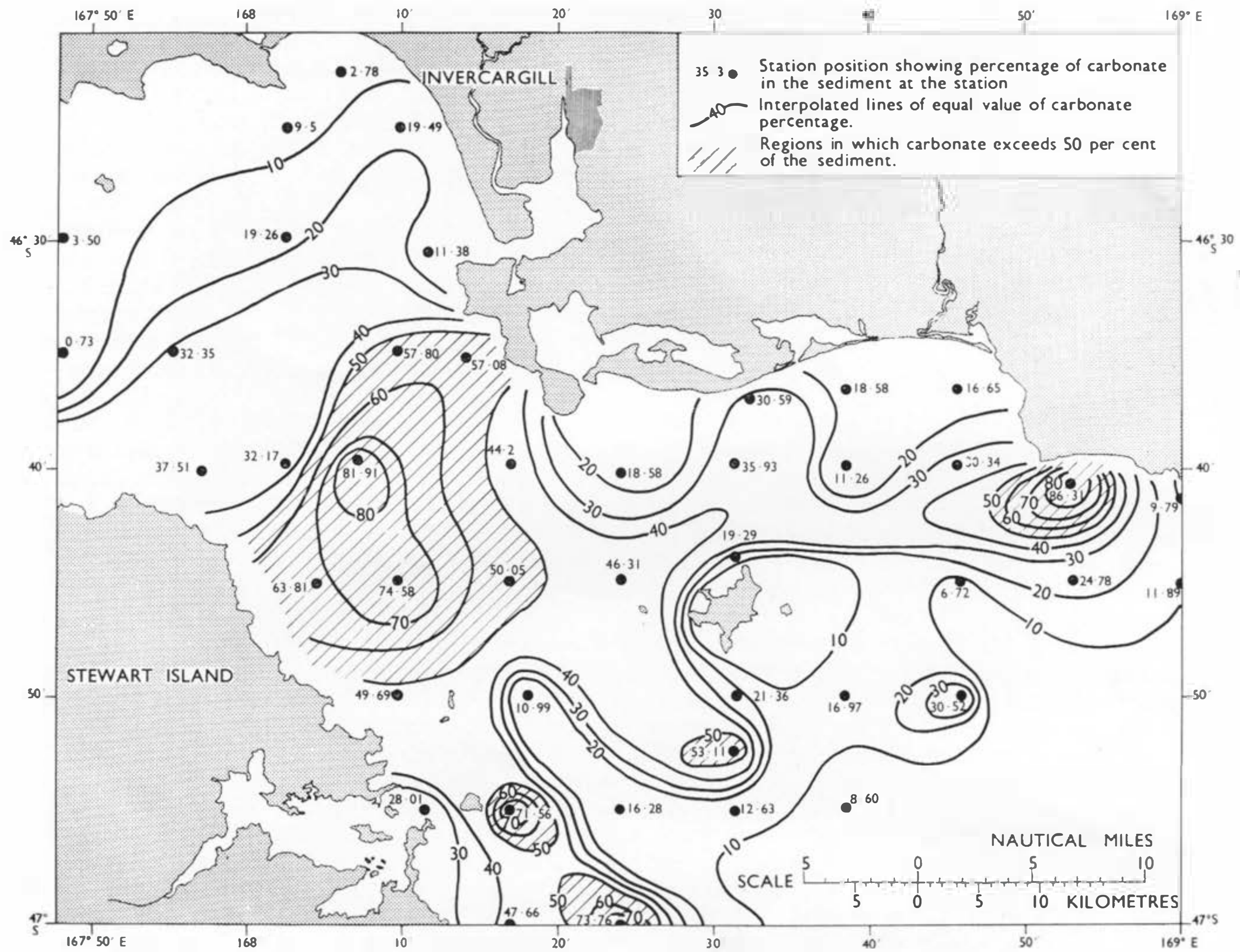


FIG. 8 Distribution of shell detritus in Foveaux Strait. Isopleths based on percentages by weight of total sediment, and interpolated at 10% intervals.

Although the distribution of shell debris in Foveaux Strait is obviously controlled by ecological, sedimentological and hydrological factors, the relative importance of these is difficult to assess. On one hand, shell detritus is derived mainly from bottom-dwelling molluscan and bryozoan communities, and to a certain extent its composition depends both qualitatively and quantitatively upon the distribution of these communities. On the other hand, the fragmentation and abrasion of robust lamellibranch valves, the dominant component of the shell detritus, provide evidence of the circulation of bottom currents capable of moving the near-flat shells and shell fragments over the floor of the Strait and of building up local shell concentrations.

A large proportion of the shell detritus in the deposits rich in carbonate is derived from infaunal molluscan species, valves of the lamellibranchs *Tawera spissa, Glycymeris modesta* and *Venericardia purpurata* being particularly numerous. These organisms depend upon the presence of fine sand, either as pockets in the widespread gravels or as thin superficial layers. Much of the epifauna also, including the economically valuable oysters and certain types of bryozoa, seem to prefer soft bottom conditions. In addition to the close relationship of the current pattern to the distribution of fine sediment in the Strait, an important part is played by comminuted shell in building up the fine sediment, so essential for the survival of the infauna and certain members of the epifauna (Cullen, 1962).

These factors give some indication of the complex interdependence of the various processes—biological, sedimentological and hydrological—in the accumulation of shell detritus.

A process of shell accumulation is envisaged involving the alternate deposition and destruction of transient layers and pockets of fine sediment regulated by periodic local changes in the current circulation, and the consequent comminution of epifaunal and exposed infaunal shell material. It is considered that sediments excessively enriched in fragmental shell are formed by prolonged winnowing of fine detritus of both inorganic and organic origin. Whereas the latter is continually replenished by further comminution of the residual coarse shell, the mineral grains are less readily replaced and become progressively depleted.

TRANSPORTATION AND DEPOSITION OF THE SEDIMENT COMPONENTS

On the basis of gross textural characteristics, five discrete classes of sediment are recognised in Foveaux Strait. Frequency curves show separately the size distribution of carbonate, and rock/mineral particles in each sample (fig. 4). The curves indicate clearly the intermingled individual detrital components that have created the sediments exposed on the floor of the Strait today. The frequency curves for B 253, for instance, show this sediment to be composed essentially of four such elements, each represented by a maximum on the curves, viz. whole and broken shell (4.0–32.0 mm), rock pebbles (4.0–16.0 mm), very coarse to coarse shell sand (0.5–2.0 mm), and medium quartz sand (0.25–0.5 mm). The combination of these components gives the sediment its polymodal character but, while the sediment as a whole is completely unsorted, the individual components are in themselves reasonably well sorted.

The frequency curves of carbonate and rock or mineral detritus show that, in all, seven discrete components can be distinguished among the sediments of Foveaux Strait (table 1).

(a) *Components of sand grade*

Many aspects of the sedimentological behaviour of the seven detrital components, and in particular the relationships between shell and rock or mineral particles during transportation, are clarified by the size-frequency curves.

In the well-sorted fine to medium sands, calcareous and mineral sands of certain grades are

TABLE 1 The rock/mineral and calcareous components of Foveaux Strait sediments.

COMPONENTS	*SIZE RANGE (mm)*	*OCCURRENCE*	*SUGGESTED MODE OF TRANSPORT*
		ROCK/MINERAL COMPONENTS	
Large pebbles	>16.0	Abundant in gravels in north-west part of Foveaux Strait.	Residual
Small pebbles	4.0-16.0	Abundant in gravels in central and eastern parts of the Strait.	Residual
Medium sand	0.25- 0.50	Rarely a dominant component as in B 270. Associated with finer sand in some gravels e.g. B 219, B 238, B 262.	Saltation
Fine-very fine sand	0.062- 0.25	The dominant component of well-sorted fine sands. Commonly an important component in gravels, often in association with medium sand.	Suspension
		CALCAREOUS COMPONENTS	
Whole and broken shell	>4.0	Rarely an important component except at certain places in main shell beds e.g. B 235, B 237, B 264.	Traction (in part)
Very coarse-coarse shell sand	0.50- 2.0	Occasionally a dominant component as in B 226, B 228, B 271. A small but almost ubiquitous component of the sands and gravels.	Saltation
Medium-fine shell sand	0.125- 0.50	Never a dominant component, but commonly associated with fine – very fine rock/mineral sand.	Suspension

frequently associated. In samples B 218, B 230, B 231, B 241, B 242 and B 261, medium to fine shell sand, with median diameters from 0.25–0.375 mm, occurs together with fine to very fine mineral sand, the median diameter of which approximates to 0.187 mm. Both the calcareous and the mineral components of these sediments were transported (it is suggested, predominantly in suspension) and deposited by the same current, and the disparity between the "equivalent" median diameters of the two components is clearly a reflection of differences in particle shape.*

A comparable association of components is encountered in the coarse, poorly-sorted sands (B 226, B 228, B 271) and in certain of the gravels (e.g. B 221, B 229, B 254, B 264). In these samples, coarse shell sand components, with median diameters between 1.0 and 1.5 mm., are associated with the medium mineral sand with diameters between 0.25 and 0.50 mm.† As coarse shell sand frequently occurs in conjunction with medium shell and fine mineral sands (B 259, B 268), it has seemingly been transported and deposited by the same currents. It could be argued that the associations of these sand-grade components is controlled by factors no more significant than their availability, but it is here suggested that the types of component present in the sediments and their proportions are regulated by the different processes by which the sediments were transported and deposited. Whereas the medium shell and fine mineral sands have been transported mainly in suspension, the coarse shell sands were moved by saltation across the sea bed. The medium mineral sand, which is so commonly associated with the coarse shell sand, is similarly part of the saltation load.

Thus, a pattern of transportation and deposition for sand-grade sediments in Foveaux Strait can be discerned. The medium to fine shell sands are thought to have been carried in suspension, together with fine and very fine mineral sands, by currents sweeping through the Strait, while the very coarse and coarse shell sands and the medium mineral sand were moved by saltation over the sea bed by the same currents.

These conditions are idealised in the frequency curves for sample B 262 (fig. 4) which show two broad but distinct peaks (at approximately 1.5 and 0.25 mm) for shell detritus, but a single negatively-skewed curve for the mineral sands, formed by the merging of data for medium (0.375 mm) mineral components, moved by saltation, and fine (0 187 mm) components, carried in suspension.

As might be expected from the heterogeneous natures of both the shell and mineral sands, deviations from normal grain-size composition are not infrequent, but the textural variations can still be related to the processes outlined above. In B 259, for instance, the saltation load of very coarse to coarse shell sand is complemented by a suspension load, somewhat finer grained than usual, of *fine* shell sand. The single-peaked curve for the mineral sand, which indicates an abnormally high proportion of very fine sand in addition to fine sand, is characterised by negative skewness and rather low kurtosis. This may be explained, as in B 262, by the merging of data relating to suspended and saltation-moved mineral components.

The areal distributions and combinations of the various sand components in Foveaux Strait are complex, but conform to a rational pattern. The coarse shell and medium mineral sands are best developed along a belt extending from the northern tip of Stewart Island through Toetoes Bay to Waipapa Point, within which major shell beds occur (fig. 9). Away from the shell beds, however, the coarse components become less prominent and the more mobile, finer sands of the suspended load predominate in surface sediments in the eastern and south-eastern regions of the Strait, also in sediments off the Oreti and Mataura estuaries (fig. 10).

*The specific gravity of calcium carbonate is somewhat higher (calcite 2.72; aragonite 2.95) than that of quartz (2.65). However, the specific gravity of fresh shell material is slightly lower than that of pure calcium carbonate, presumably because of its organic content, the mean of several measurements being 2.69. In the case of shell subjected to submarine weathering the effective density is further lowered by the increased porosity.

†The ratio of diameters of complementary shell and mineral particles in the well-sorted fine sands is approximately 1.33:1.0; in the coarse sands the ratio is 2.66:1.0. This apparent anomaly may be attributed in part to the different modes of transport involved, but more to the contrasting differences in shape between the shell and mineral particles. Whereas the latter tend to be equidimensional, roughly tabular shapes predominate among the shell fragments. Surface area is relatively larger for the shell fragments, and seems to be the factor controlling their mobility, while the transportability of the mineral grains is proportional to their volume.

The ratio, calculated from the observed particle diameters,

$$\frac{\text{Volume Mc}}{\text{Area Sc}} : \frac{\text{Volume Mf}}{\text{Area Sf}} \text{ is approx. } 2:1$$

where Mc, Sc are mineral and shell grains of coarse sand grade, and Mf, Sf are equivalent components of the fine sand.

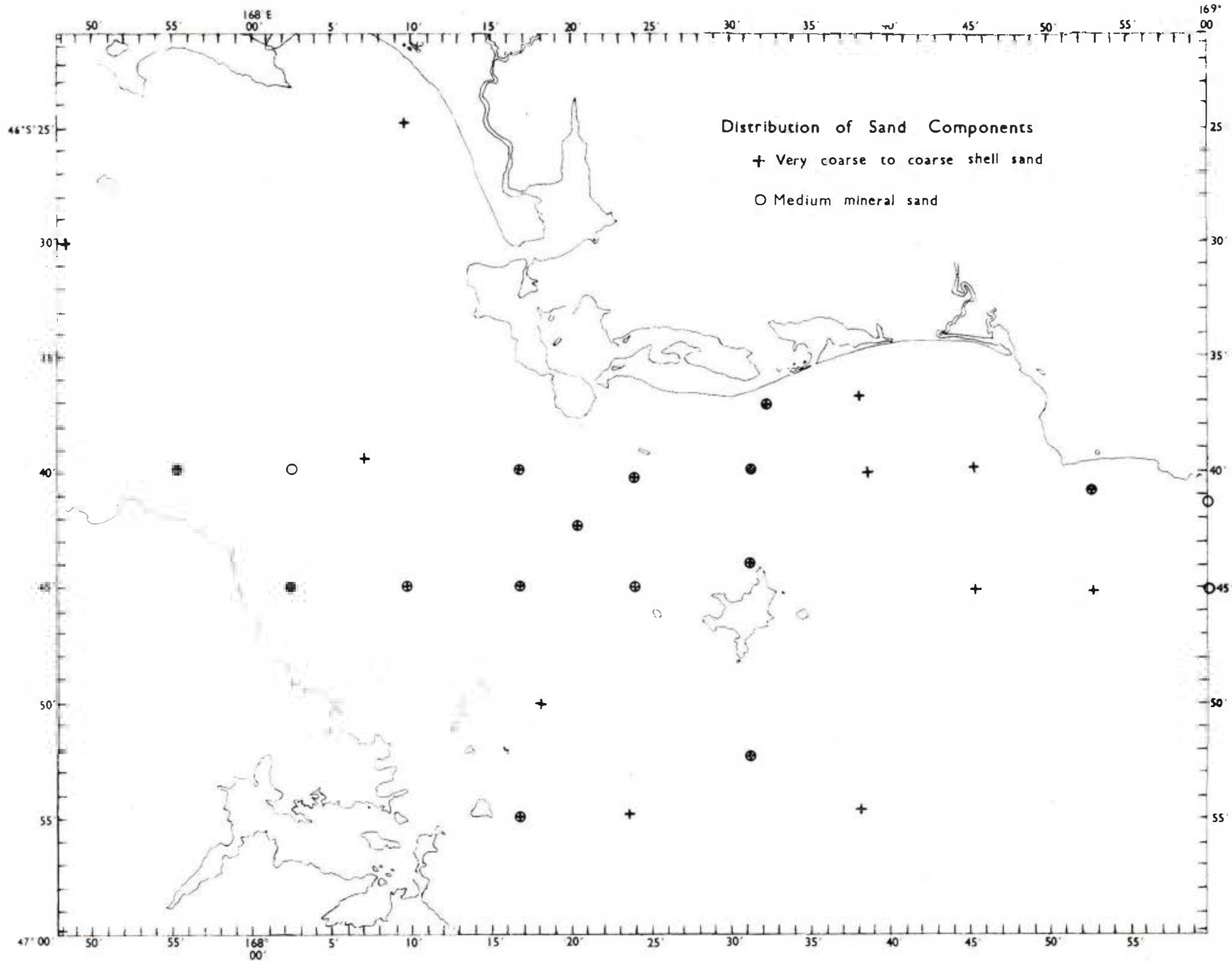


FIG. 9 Distribution of the coarse shell/medium mineral sand association in Foveaux Strait, indicating stations at which these components are represented by maxima on the frequency curves.

(b) *Pebble components*

In table 1, the rock pebbles, both large and small, are described as residual, in that they are not considered to be representative of the contemporary sedimentary regime in the Strait. Currents of 2–2½ knots, such as are locally recorded in the Strait, are capable of moving pebbles up to 10 mm in diameter (Hjulstrom, 1939), but it is considered that the lateral transport of pebbles of such size in Foveaux Strait is small, and likely to be neutralised by reversal of tidal streams. In fact, it is doubtful whether particles of this size are subjected to more than local jostling to and fro under existing conditions

Consideration of the petrology of the submarine gravels, and of the particle-size distribution in terrace gravels of the Southland Plain adjacent to Foveaux Strait (see below), suggests that the pebbles are basically of fluviatile origin, deposited in a terrestrial environment during a past low stand of sea-level.

(c) *Whole and broken shell greater than 4.0 mm*

In the size-frequency curves for a number of samples (e.g. B 235, B 238, B 253, B 264), a feebly developed peak can be detected, corresponding to shell grades from 8.0–16.0 mm. The materials of this component are very varied, both in state of preservation and biological composition, and include fresh whole shells, worn, weathered and ironstained whole shells and shell fragments ranging from fresh to thoroughly weathered.

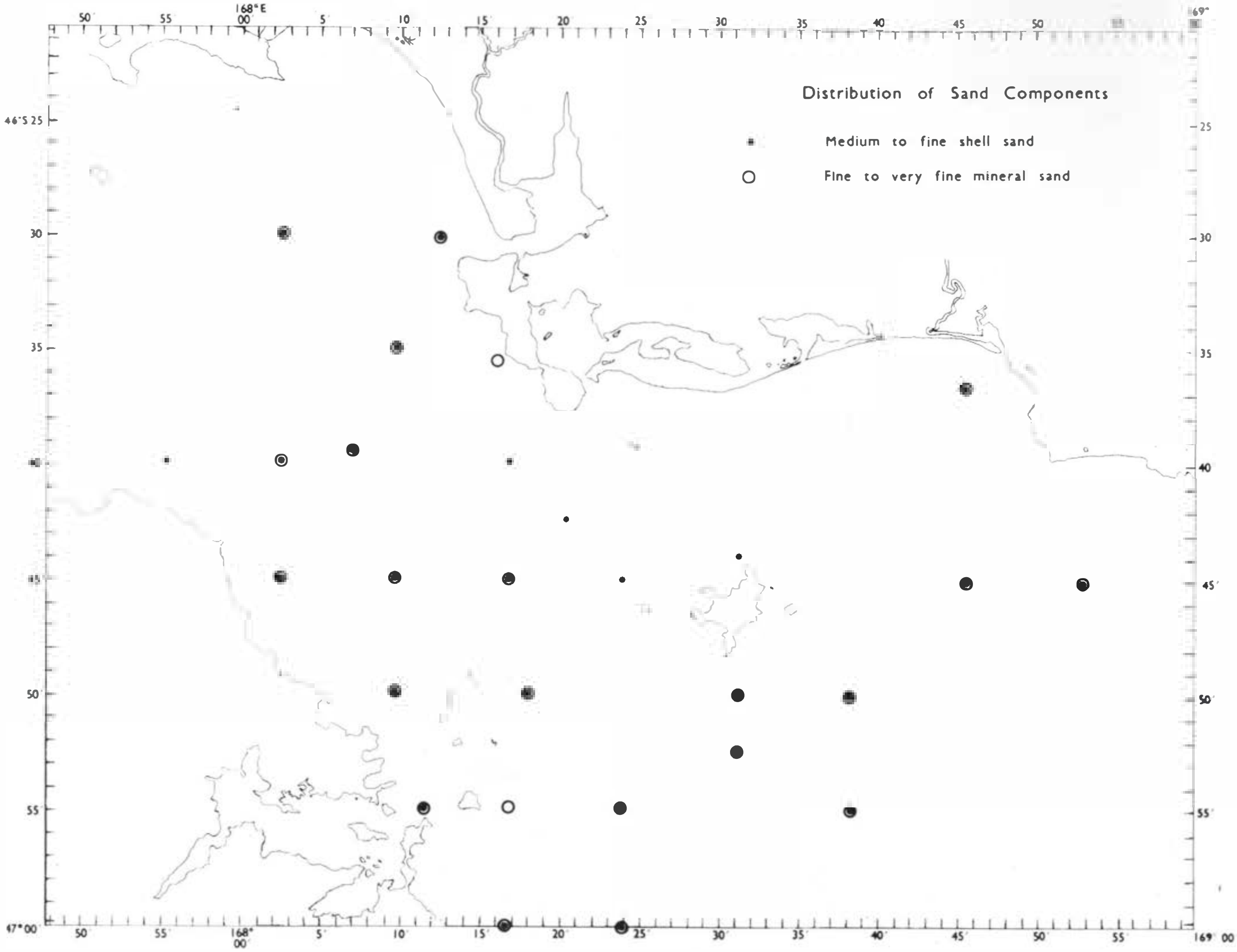


FIG. 10 Distribution of the medium shell/fine mineral sand association in Foveaux Strait, indicating stations at which these components are represented by maxima on the frequency curves.

Molluscan remains are dominant, (especially valves of *Tawera*, with less frequently *Glycymeris* and *Venericardia*), and bryozoan skeleta and barnacle plates are also common.

Transportation is clearly responsible for intermingling these diverse organic particles and, by analogy with the coarse and medium shell sand components, shell between 8.0 and 16.0 mm is regarded as detritus moved over the sea bed by traction.

There is, however, no obvious complementary peak in the rock and mineral size-frequency curves, that can be attributed to traction transportation. Very coarse mineral sand, granules and small pebbles (from 1.0 mm–>4.0 mm), which are of the most suitable size to be moved by this means, do not figure in the curves for the finer sediments. In the bimodal frequency curves of the coarser deposits they are typically represented by minima of very low value. Only in samples B 228 and B 257 is there a hint of a peak in the 1.0–2.0 mm range.

Shells greater than 32.0 mm are encountered in some samples, and in B 238 a prominent peak in the size-frequency curve (quite distinct from that denoting the 8.0–16.0 mm shell component) coincides with the 32.0–64.0 mm size range. Oyster valves are prevalent in this class of shell. Although solution pitting and the depredations of boring organisms are sometimes visible, these large shells show little evidence of transportation, and delicate encrusting bryozoa and articulated barnacle plates still adhere to their relatively unworn surfaces. It is apparent that the size of such shells has no direct sedimentological significance, but merely indicates the stage of growth reached by the organisms before death.

(d) *Mud*

Quantitatively, sediment of mud grade is unimportant in Foveaux Strait and at only three stations (B218, B 230, B 237) does it exceed 5% by weight of the total sample. Like the fine sand (already discussed) the mud is believed to exist as a transient veneer upon the sea-floor, and as such it probably exerts a profound influence upon the ecology of those regions where it occurs in appreciable amounts.

The distribution of mud in Foveaux Strait is shown (fig. 7) to have high-value focal points close to Paterson Inlet and the Oreti River, comparing in this respect with the distribution of fine and very fine sand (fig. 6). Both patterns are clearly related to river outfall and known present-day current trends within the Strait, and it is evident that the mud and fine sands have very similar sedimentological behaviour. Two basically opposed interpretations of the distribution patterns of mud and fine sand can be made. Either the patterns signify the encroachment of the mud and sand over a basement of predominantly coarser sediments, or they may indicate erosion of an originally widespread mud and fine sand veneer. Neither of these hypotheses provides a complete explanation. but there is ample evidence that both depositional and erosional processes operate within quite well-defined areas of the Strait. Mud and fine sand emerging from the Oreti estuary are swept south-westward by currents and deposited within a zone that extends almost to the Stewart Island coast. Currents near Paterson Inlet, however, carry the fine detritus north-eastward and deposit it as a long tongue projecting to the centre of the Strait. Along a narrow belt extending from the northern tip of Stewart Island to Waipapa Point erosion is active, and fine sediment is swept away to accumulate in the deeper waters east of Foveaux Strait.

THE SUBMARINE GRAVELS OF FOVEAUX STRAIT

PETROLOGY

Before describing and discussing the petrology of the gravels in Foveaux Strait, it is pertinent to give a brief account of the rock formations on the adjacent land (fig. 11) so that the significance of pebble distributions may be better appreciated.

OUTLINE OF THE GEOLOGY OF LAND BORDERING FOVEAUX STRAIT

The mountainous terrain of Stewart Island to the south of the Strait is composed of granite, gneiss, schist and migmatite (Williams, 1934) of presumed Paleozoic age, similar in many respects to rocks that occur in the Fiordland region far to the north-west. Small masses of granite are known also along the northern shore of the Strait, but their size is negligible and none could seriously be regarded as a major source of granite pebbles.

Synclinally-folded, late Paleozoic and Mesozoic greywackes and argillites underlie much of Southland, but on the monotonously flat Southland Plain these solid formations are concealed beneath Tertiary sediments and thick Quaternary fluviatile gravels. The latter extend southward to form the greater part of the northern shore of the Strait. North of the greywacke outcrop lies a wide belt of Chlorite-zone schists, which strike south-east to the Otago coast, but nowhere approach Foveaux Strait.

The islands in the northern part of the channel, and rocky stretches of the northern shore at Bluff promontory and between Pahia Point and Riverton, are composed of a suite of late-Paleozoic ultrabasic and intermediate intrusive igneous rocks, the Longwood-Bluff Intrusives (Service 1937: Reed, 1948: Harrington and McKellar, 1956). Minor outcrops of similar rocks have been reported recently (Watters, 1962) from north-eastern Stewart Island. Associated with the intrusives to the north of the Strait, but much less widely exposed, are basic and intermediate volcanics also of late - Paleozoic age.

The outcrops of the intrusive and volcanic rocks delineate the southern flank of the Southland Syncline, but in contrast to similar formations that extend along the northern flank of this structure (Wood, 1956), there is no evidence that they are associated with greywackes and argillites.

Indeed, the absence of greywacke outcrops among the islands at the eastern end of the Strait, and the proximity of the intrusive rocks to basement metamorphics in the region, suggest either that greywackes are not present beneath the Strait, or that their buried extension is very much attenuated. Whether this effect is due to elimination of the greywackes and argillites by strike-faulting parallel to the axis of the Strait, to the thick development of volcanics at the expense of the greywackes, to the incorporation of greywackes in the Stewart Island migmatite complex, or to a combination of all these possibilities, is still undecided. However, in this discussion the significant point with regard to the provenance of the sediments is the absence of a known source of greywacke and argillite within the region occupied by the Strait itself.

PEBBLE ASSEMBLAGES IN THE GRAVELS OF FOVEAUX STRAIT

A generalised petrological examination was made of the rock and mineral components of the sediments from Foveaux Strait in an attempt to determine their provenance, mode of transportation and depositional history.

Particular attention was given to the pebbles and cobbles in the gravelly sediments since these had proved to be so widely distributed, and clearly offered the best opportunities for establishing petrological relationships with rock formations exposed on the land to the north and south of the Strait. The rocks occurring as pebbles and cobbles can be classified into four distinct and easily recognisable lithological assemblages:

(a) The greywacke - argillite - breccia assemblage.
(b) The granite - gneiss assemblage
(c) The porphyrite - diorite assemblage
(d) The quartz - quartz-chlorite schist assemblage

Each assemblage corresponds to an established formation or group of formations on the neighbouring land. The number of pebbles that could not be accommodated in one or other of

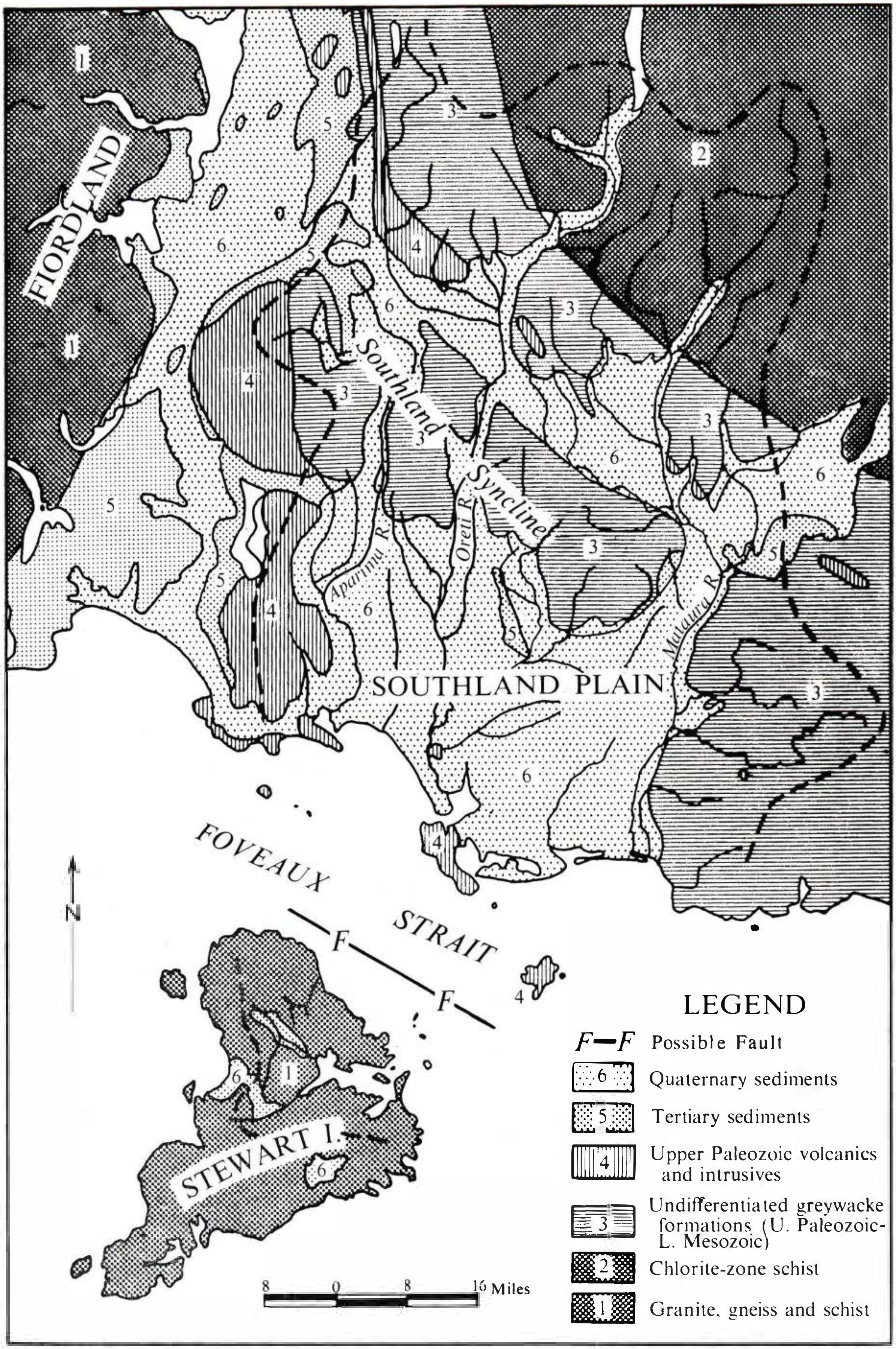


FIG. 11 Simplified geological map of the land adjacent to Foveaux Strait (modified from the Geological Map of New Zealand, N.Z. Geological Survey, 1958).

these assemblages was negligible and limited for the most part to unidentifiable individuals composed of sheared varieties of rock.

The classification of the majority of large and medium-sized pebbles was relatively simple, particularly after detailed petrographic examinations of representative rocks from each assemblage. For fine-grained varieties and some of the small pebbles, where the mineralogical and textural features could not be clearly seen with unaided vision, it was found helpful to immerse the pebbles in water in a petrie dish while examining them under a binocular microscope.

(a) *The greywacke - argillite - breccia assemblage*

The rocks that occur in greatest abundance and have the widest distribution in the submarine gravels of Foveaux Strait are those belonging to the greywacke - argillite - breccia assemblage. Over much of the Strait they comprise 50% or more of the pebbles and cobbles and, as they themselves are normally coloured dark green, brown or grey, they impart an overall dark colouration to the gravels in which they occur.

The primary source of the greywackes, argillites and breccias undoubtedly lies in the thick formations of late Paleozoic and early Mesozoic age, so extensively exposed today to the north of the Strait in Southland and southern Otago. Particularly characteristic are rock types that resemble very closely sediments of the Permian Maitai Series and the (?) Upper Carboniferous Te Anau Group described by Grindley (1958).

The pebbles of *Maitai-type* rocks are composed mostly of dark green and greenish-brown feldspathic and lithic greywackes and dark green to pale greenish-grey argillites. The greywackes consist essentially of crudely-sorted, angular fragments of feldspar, quartz and fine-grained, indurated sedimentary and volcanic rocks within a matrix of chlorite and other clay minerals. The same components are present in the argillites, but rock fragments are much less common, and only minute fragments of the finest-grained types occur. Sedimentary banding, due to alternating layers of fine and relatively coarse detritus, is a typical feature of the argillites. A variety of lithic greywacke that is widely distributed in the Foveaux Strait gravels contains conspicuous fragments of pink, red, yellowish-grey and greenish-grey argillite, and is very similar to certain of the Maitai greywackes described by Grindley (1958) from exposures in the Eglinton Valley, 60 miles north of the Strait.

The pebbles of *Te Anau-type* rocks are broadly similar in lithology but tend to be darker coloured, the greywackes being typically dark grey, and the argillites black with a siliceous 'flinty' appearance. Some distinctive breccias and microbreccias that occur as scarce but very conspicuous pebbles are probably related to these greywackes and argillites. The breccias contain fragments of red and green tuffaceous argillite and vesicular and amygdular volcanics, closely resembling breccias found in the Livingstone Volcanics of the Te Anau Group (Grindley, 1958).

(b) *The granite-gneiss assemblage*

Second in importance to the greywackes and argillites in the Foveaux Strait gravels is an assemblage of crystalline rocks that includes various types of granite and gneiss and also some amphibolites. In many of the gravel samples, these rocks comprise over 25 per cent of the pebbles, their predominantly pale colour and their textures distinguishing them from the pebbles of greywacke and argillite.

The granitic rocks include alkali leucogranites, adamellites and granodiorites, ranging in colour from white to medium grey on fresh, newly-broken surfaces. However, because of superficial staining of the feldspars, and to a lesser extent of the quartz, by hydrated iron oxide, the external colouration of the granite pebbles normally ranges from orange-yellow to brown.

The leucogranites, which are by far the most abundant variety in this assemblage, are mostly potassi-sodic in composition and contain microcline and orthoclase in excess of oligoclase. Many are characterised by granophyric texture, whilst a distinctive garnetiferous aplogranite, containing numerous euhedral and subhedral pink garnets from 0.5–1.0 mm in diameter, occurs as a minor constituent in many of the gravel samples. Because of their content of ferromagnesian minerals (principally biotite and hornblende) the adamellites and granodiorites are noticeably darker than the alkali granites. The higher proportion of plagioclase in them is, of course, apparent only in thin section.

Pebbles of adamellitic and granodioritic gneisses are also frequently present in the Foveaux Strait gravels. Their structure is emphasised by the alignment of ferromagnesian minerals but their composition is otherwise identical with the non-gneissose granites.

A migmatite complex that includes granites and gneisses petrographically identical with varieties found in the Foveaux Strait gravels is extensively exposed along the northern coasts of Stewart Island, and it is not necessary to look further afield for a provenance for the pebbles of the granite - gneiss assemblage.

Alkali-granites have been reported also along the northern coast of the Strait. Narrow dykes of biotite granite are exposed near Bluff—at Tewaewae Point and in the vicinity of Ocean Beach (Service, 1937)—while a similar rock occurs at Mullet Bay near Pahia Point in the extreme north-west of the Strait. It is highly improbable, however, that these small, isolated masses could have contributed significant volumes of granitic detritus to the gravels.

Lithological comparisons can also be made between the granitic pebbles in the submarine gravels of Foveaux Strait and rocks exposed in the Fiordland region of South Island, to the north-west of the Strait. In one interesting example, a distinctive garnetiferous leucogranite that occurs in the gravels can be matched not only with rocks exposed at Port William on Stewart Island (Williams, 1934; W. A. Watters, pers. comm.), but also with certain facies of the Pomona Granite of Fiordland. While it would be unwise to discount entirely the possibility that some of the granite and gneiss pebbles are derived from the north-west (and even perhaps from areas now submerged to the west of the Strait), the most feasible source for the majority of granite and gneiss pebbles in the Foveaux Strait gravels is Stewart Island.

Provisionally included in the same assemblage as the granites and gneisses is another group of pebbles of amphibolitic and quartzitic composition that occur, although rarely, in the gravels. The situation is, however, complicated by the possibility that amphibolites of more than one type may be present and while some are without doubt petrogenetically related to the Stewart Island migmatites, others may have been derived from the amphibolite suite associated with the Bluff Intrusive Series on the northern shores of the Strait (Service, 1937). Pebbles of amphibolite are so few as to be statistically negligible, and in the present study it has not been necessary to attempt a more detailed petrographic subdivision.

The amphibolites are dark, compact, fine-grained rocks, not readily distinguishable as pebbles from certain types of dark argillite. In thin section, however, the difference is pronounced, the amphibolites consisting almost entirely of green hornblende and andesine, often but not always showing parallel orientation, with fine granular iron ore as the main accessory.

The quartzites included in the granite - gneiss assemblage are grey, finely-granular siliceous rocks, usually stained brown superficially and enclosing minute orientated flakes of biotite that impart a faint "schiller" effect to the pebbles. They should clearly be grouped with the high-grade metamorphics of Stewart Island, and Williams (1934) has recorded identical rocks in that region.

Excluded from the granite - gneiss assemblage are pebbles of tonalite which occur in small quantities scattered throughout the gravels. Despite their pale colour and superficial similarity to certain of the granites, the tonalities are closely related to rocks of the Bluff Intrusive Series and are included with them in a separate assemblage.

(c) *The porphyrite-diorite assemblage*

Compared with pebbles of the greywacke-argillite and granite - gneiss assemblages, porphyrites and diorites occur in the Foveaux Strait gravels in very subordinate amounts. Although present in most of the gravels collected, the porphyrites and diorites comprise numerically less than 10% of the pebbles in the majority of samples, and in only two areas—off the extreme northern tip of Stewart Island and to the west of the Oreti estuary—do they exceed 20%.

The assemblage is composed of a variety of distinctive rocks of volcanic and hypabyssal aspect, here grouped together since they are lithologically similar, and undoubtedly equivalent, to extrusive and intrusive rocks that occur in intimate association on the mainland north of the Strait.

Typically, the porphyrites and diorities are compact melanocratic rocks distinguished from amphibolites and from dark types of argillite by unmistakable igneous textures—for the most part apparent to the naked eye.

The porphyrites are normally dark grey, brownish-grey and greenish in colour, with euhedral to subhedral phenocrysts (up to 2.0 mm across) of pale feldspar and, less commonly, dark ferromagnesian minerals, clearly visible in a fine-grained matrix. The extrusive nature of some of the porphyrites is indicated by the sporadic occurrence of vesicular and amygdular structures and by crude flow alignments of the phenocrysts themselves. However, it is still possible that porphyrites lacking these features may have originated as dyke rocks. In thin sections, the porphyrites are seen to be predominantly of andesitic and basaltic composition, with feldspars ranging from basic oligoclase to labradorite, although some less common, paler coloured varieties have been identified as trachyandesites and feldsparphyric microsyenites. Augite is the normal coloured silicate, and secondary chlorite, epidote and bastite also occur. The groundmass is not infrequently hyalopilitic, with glass occupying the interstices between plagioclase microlites, and its dark colour is often accentuated in the more basic varieties by disseminations of finely granular magnetite or ilmenite.

While the dioritic pebbles differ markedly from the porphyrites in texture and in their coarser grain size, mineralogically there are some similarities. The feldspars lie mainly in the oligoclase-andesine range, and common hornblende and clinopyroxene are the most typical mafic minerals, although brown lamprobolite (basaltic hornblende) has been observed in a few of the microdiorites. Some pebbles of a more basic gabbroic rock, containing labradorite and abundant clinopyroxene also occur and are included in the porphyrite - diorite assemblage. The occurrence of a faintly pleochroic orthopyroxene in some varieties suggests affinity with the noritic rocks exposed on Bluff Peninsula and described in detail by Service (1937). The presence of leucocratic and mesocratic tonalites in the gravels and their similarity in appearance to granites have already been mentioned. Pebbles of tonalite can be distinguished from granite, however, by their lack of visible quartz in hand-specimen—with which is associated a tendency to smoother-worn surfaces—and the occurrence of large stumpy crystals of greenish-black hornblende.

The textures of the dioritic and gabbroic rocks are somewhat variable, the coarse types being usually xenomorphic or hypidiomorphic granular, with gneissic banding not infrequently conspicuous both in hand specimen and thin-section. Many of the medium-grained varieties possess ophitic texture likewise visible in hand specimen, and some pebbles that show this texture are in fact composed of typical dolerite.

The petrology of pebbles of the porphyrite - diorite assemblage leaves little doubt that their primary source lay in the Longwood - Bluff Intrusive Series and in the associated volcanics of the Greenhills and Riverton areas, all of which were presumed by Service (1937) to be of late Paleozoic (L. Permian and U. Carboniferous) age. These formations are currently exposed along the northern shores of the Strait between Pahia Point and Riverton—whence they extend inland towards the Takitimu Mountains —reappearing as outliers at Bluff Peninsula and Ruapuke I. and probably forming some of the smaller islands and islets in the northern part of the Strait. Almost certainly these separate outcrops are connected by submerged and buried extensions beneath the Strait, and Benson (*in* Williams, 1934) has even suggested a connection with gabbroid rocks exposed in the north-east of Stewart Island, around the entrance to Paterson Inlet.

In view of the wide extent of the intrusive and volcanic rocks in the region of Foveaux Strait, it is surprising that they contribute so few pebbles to the submarine gravels. A possible explanation for this apparent anomaly is given later.

(d) *The quartz - quartz-chlorite schist assemblage*

Pebbles of quartz and quartz-chlorite schist are less widely distributed in Foveaux Strait than pebbles of the preceding assemblages. Although abundant in the gravels of Toetoes Bay and the north-eastern part of the channel—where they comprise over 70% of the pebbles at Sta. B 257—quartz and quartz-chlorite schist are completely absent from the southern and western sectors of the Strait.

The petrology of representative members of the assemblage is simple. Quartz, milky-white when fresh but usually stained brown by iron oxide, is by far the dominant mineral, many of the pebbles being in fact virtually monomineralic and composed of little more than a granular mosaic of quartz. Traces of crystal faces can sometimes be seen in "drusy" cavities in the pebbles, but nowhere is the crystal form of the quartz sufficiently well developed to determine whether the α or the β phase is present. While much of the quartz appears to be of vein type, a number of the pebbles have lamellar and rodded structures of cataclastic origin and in this respect are more closely related to the quartz-chlorite schist.

The quartz-chlorite schist preserved as pebbles is a highly quartzose rock with only thin, widely-spaced laminae (up to about 2.0 mm thick) of greenish-grey chlorite schist. Presumably the source rocks originally provided more highly chloritic types also, but the disintegrating processes that operated during sedimentary transportation have allowed only the more resistant quartzose material to become incorporated in the Foveaux Strait gravels.

The quartz and quartz-chlorite schist pebbles closely resemble rocks that are widespread among the Chlorite-zone schists of Otago. Although Toetoes Bay is 50 miles from the nearest present-day exposures of schists, these low-grade metamorphic rocks are regarded as the ultimate source of quartz and quartz-chlorite schist pebbles.

Restricted to the gravels of the north-eastern sector of the Strait, and hence included for convenience in the quartz - quartz-chlorite schist assemblage, are some relatively scarce rocks of quite different aspect. They are grey fine-grained, micaceous sandstones, showing occasional traces of cross-bedding and noticeably less indurated than the pebbles of Paleozoic greywacke and argillite. They occur as slabs and irregularly-shaped blocks up to 10.0 cm across, with somewhat rounded edges but bearing no evidence of prolonged transportation or severe abrasion. The sandstone is indistinguishable from certain arenites of Jurassic age exposed locally in the coastal cliffs and hinterland east of Toetoes Bay, and the slabs and blocks are almost certainly derived from these Mesozoic strata.

SEDIMENTATION

DISTRIBUTION OF THE PEBBLE ASSEMBLAGES AND THE SEDIMENTARY HISTORY OF THE GRAVELS

Method

A generalised classification of the rock types in the gravels having been decided upon, all samples containing suitable quantities of pebbles were examined. Pebbles in each grade were identified, grouped in the appropriate assemblages and counted. An average of approximately 450 pebbles was examined and categorised from each gravel sample, although an initial count of between 1,500 and 3,000 pebbles from each of five large samples was made to test the consistency of the method. In three gravel samples only were there insufficient pebbles for statistically reliable results, but even in these it was possible to obtain a fair indication of the proportions of the different assemblages.

In each sample the relative proportions of the lithological assemblages remained practically constant throughout the various pebble grades, and only smaller particles with diameters less than 4.0 mm showed any departure from this trend. In these the proportion of the granite-gneiss assemblage in some samples was slightly low compared with values in the coarser grades, no doubt reflecting a tendency for the coarsely granular varieties of granite to disintegrate completely as they approached a certain minimum size. Indeed, freshly broken angular fragments of granite have been observed among the smallest pebble and granule fractions in several samples. Examination of particles less than 4.0 mm in diameter was therefore avoided whenever practicable because of this, and also because of difficulties in handling and identification, and was only undertaken in samples where larger pebbles were present in insufficient quantities.

Results

The results of the petrological analyses of the gravels are summarised (Appendix and fig. 12), the proportions of the four lithologic pebble assemblages being represented at each station by appropriately-sized sectors of a pie diagram.

More instructive perhaps are the distribution maps (figs 13–16) in which the assemblages are considered individually. The percentage of each pebble type is plotted for each station, and isopleths interpolated on the map to show intervals of 5%. Not only do these maps indicate the spatial variations in the proportions of the pebble types, but they also facilitate interpretation of the provenance and sedimentary history of each category of pebble.

In making such interpretations it should be borne in mind that the distribution patterns have been constructed from analyses of samples taken from the *surface* only of the floor of Foveaux Strait. Nothing is known as yet of the thickness of the gravels or their petrologic variations at depth, although some suggestions are made later as to the sequence of deposition of the pebble assemblages.

It seems probable that certain of the pebbles have long and complex depositional histories, and have passed through a number of sedimentary cycles. White quartz pebbles, for instance, are common in Tertiary and Pleistocene gravels of Southland, as well as in the Recent sediments of Foveaux Strait. Under such circumstances, distributions may integrate the effects of several different cycles; a possibility that has to be considered when making interpretations.

Willett (in Couper, 1951) mentions complete *in situ* decomposition of non-quartzose pebbles, presumably under sub-aerial conditions, in some of the older terrace gravels of the Southland Plain. The possibility that the submarine gravels of Foveaux Strait may have been affected in this way, perhaps during an earlier sedimentary cycle or a former phase of low sea-level, must not be overlooked, as the elimination of certain classes of pebbles by such processes could lead to

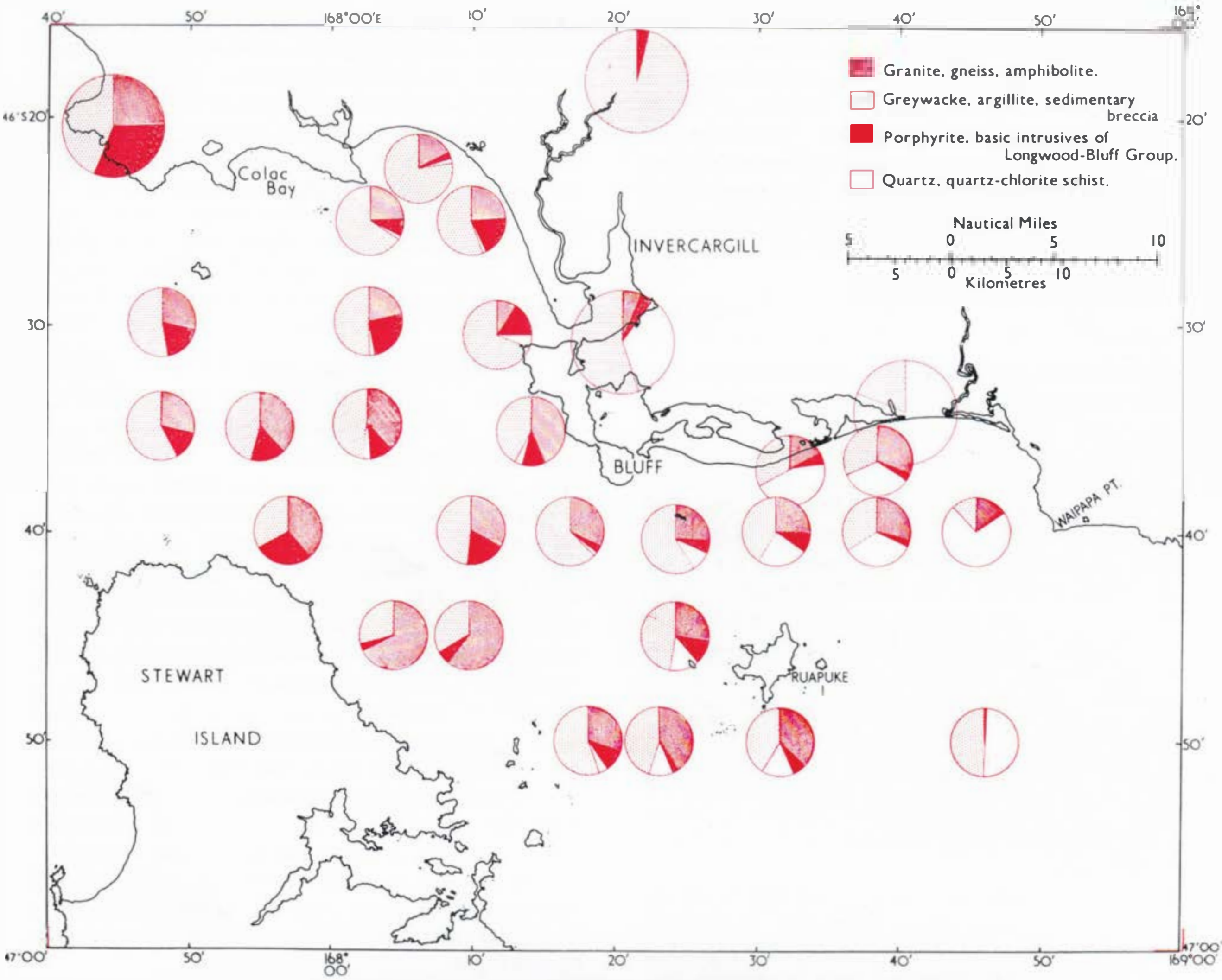


FIG. 12 Map indicating proportions of the pebble assemblages at relevant stations in Foveaux Strait. Station positions lie at the centres of the pie diagrams.

erroneous interpretation of provenance of the gravels.

INTERPRETATION OF DISPERSAL PATTERNS

(a) *The greywacke - argillite - breccia assemblage*

The distribution pattern of greywacke, argillite and breccia pebbles (fig. 13) constructed by the above method corroborates the earlier suggestion, based upon lithology alone, of a northern provenance for the assemblage. The high proportion of greywacke and argillite pebbles in the northern and central regions of the Strait, and their progressive decrease as the Stewart Island coast is approached, are both emphasised by the isopleth map.

The concentration and radial distribution of greywacke and argillite pebbles, around the entrances of certain rivers and lagoons along the northern shore of the Strait, is particularly noticeable off the Oreti River estuary and near the entrance to Bluff Harbour. Indeed the distribution pattern for the entire central and eastern sectors of the Strait appears to radiate from the Bluff Harbour entrance.

It is thus not difficult to visualise a close association between the distribution of the greywacke - argillite assemblage and the terrestrial drainage north of the Strait. The alternative possibility, that the distribution reflects a pattern of submerged greywacke and argillite outcrops, is unsupported by any evidence, although it is not improbable

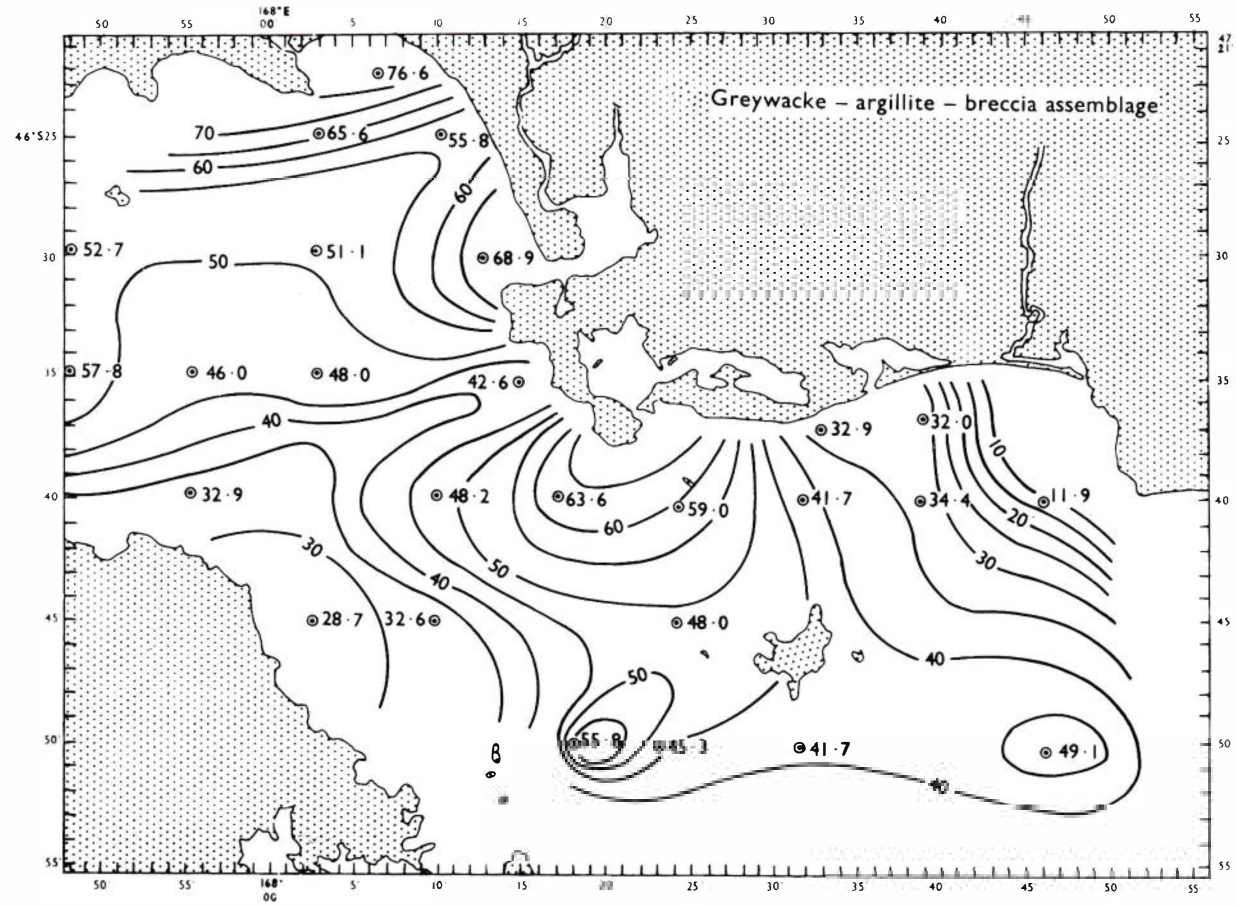


FIG. 13 Distribution of the greywacke – argillite – breccia assemblage. Isopleths based on the percentages of total number of pebbles at each station, and interpolated at 5% intervals.

that greywacke formations occur at depth below the submarine gravels in the northern part of the Strait at least. Nor can present-day tidal streams be held responsible for the basic distribution since the pattern indicates a spread of the pebbles across the Strait in directions perpendicular to the trends of these currents. However, localised east-west bulges in the isopleth pattern may be explained by a limited redistribution of pebbles by contemporary water movements.

At the present day, only fine sediment enters the Strait by way of the rivers and lagoons and it is therefore presumed that the distribution of greywacke and argillite pebbles is related to an ancient drainage system that operated when the sea-level was lower and the rivers more vigorous. It can be assumed that the basic distribution of the submarine pebbles was effected by the same fluviatile agencies that were responsible for the deposition of the Pleistocene and Quaternary gravels on the neighbouring land. Petrological analyses of a small number of terrestrial gravels, collected from regions of the Southland Plain bordering the Strait, indicate abnormally high concentrations of greywacke and argillite in the gravel spreads north of Bluff and Invercargill.

In Toetoes Bay the proportion of greywacke and argillite pebbles in the submarine gravels is exceptionally low, some of the gravels in the vicinity of Waipapa Point containing less than 12% of pebbles of this assemblage—the lowest value in the entire Strait. It would seem that the transportation and deposition of the gravels in this region were accomplished by a completely different river system, presumably the Mataura River or its predecessor, and that this river tapped a source area in which greywacke and argillite detritus was not available in appreciable quantities.

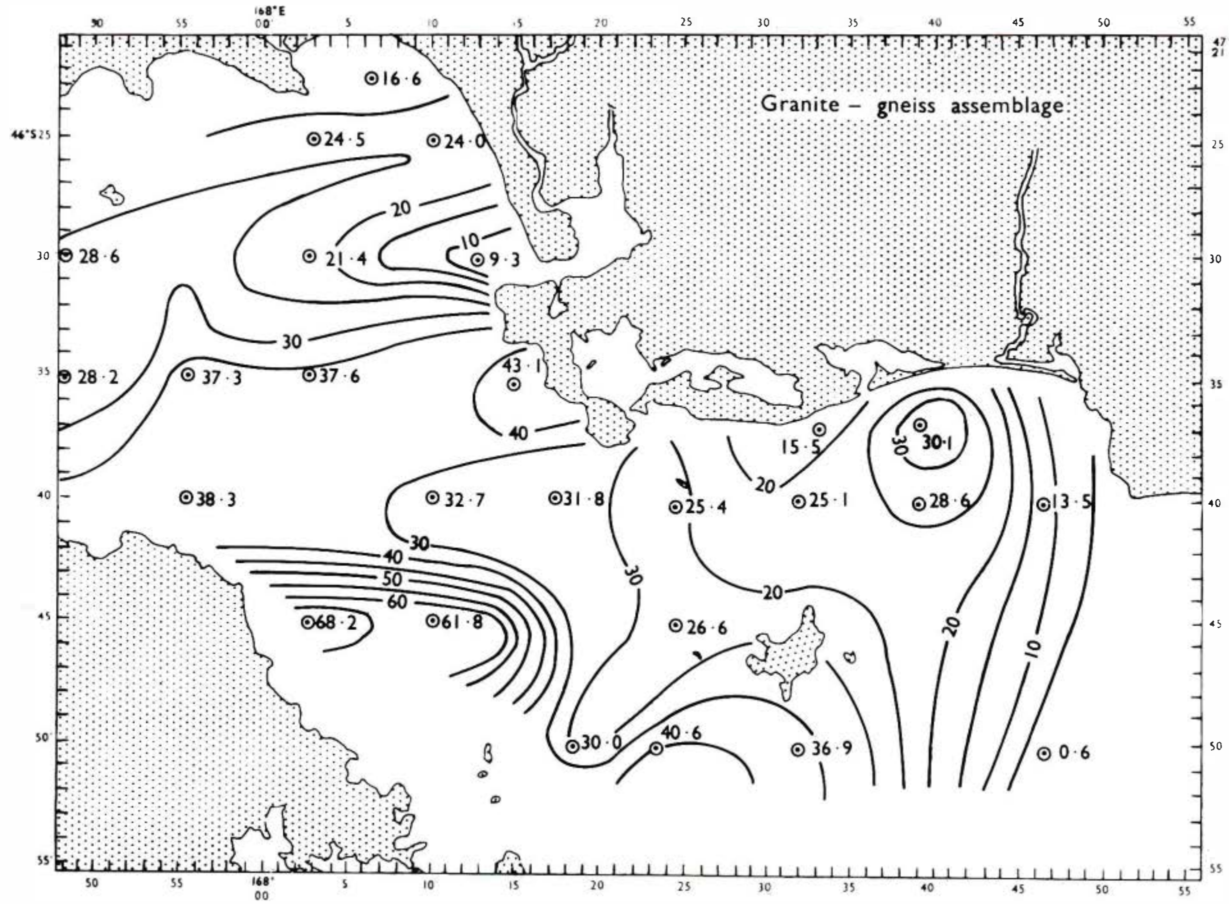


FiG. 14 Distribution of the granite – gneiss assemblage. Isopleths based on the percentages of total number of pebbles at each station, and interpolated at 5% intervals.

To summarise, it is envisaged that the greywacke and argillite pebbles were transported to the site now occupied by Foveaux Strait by large, vigorous rivers (the proto-Oreti and proto-Aparima) descending from the regions north of Invercargill and Riverton during the Pleistocene and early Holocene. Since the sea-level was lower at that period, these rivers could have traversed and helped to aggrade broad alluvial plains in the region between Stewart Island and the Bluff - Riverton area. That the range of hills forming Bluff Peninsula obstructed the southward movement of the greywacke and argillite pebbles is suggested by the relative sparsity of this type of pebble in the submarine gravels near the south-western ("lee") flank of the Peninsula.

(b) *The granite-gneiss assemblage*

Since the granite - gneiss and greywacke - argillite assemblages together comprise over 75% of the pebbles in the majority of Foveaux Strait gravels, the distribution pattern of the granitic and gneissic pebbles (fig. 14) is to a large extent complementary to that of the greywackes and argillites.

The highest proportions of granitic pebbles occur in the gravels off the north-east coast of Stewart Island, and particularly in the vicinity of Saddle Point and the Murray River where 68% of the pebbles at Sta. B 228 belong to the granite-gneiss assemblage. To the north and east of this locality values decrease abruptly to average from 20–40% over most of the Strait while, to the east of Ruapuke I., granite pebbles dwindle to less than 10% at Sta. B 267. This distribution pattern confirms the Stewart Island region as the main source of the granite - gneiss assemblage.

As might be surmised from previous discussion, granite pebbles become sparse around the river estuaries and harbours opening into the northern part of the Strait being numerically overwhelmed at these points by the abundance of north-derived pebbles, especially of greywacke and argillite. Patches and tongues of gravel containing somewhat higher proportions of granitic pebbles occupy the intervening areas near the northern shore of the Strait, as for instance to the south-west of Bluff Peninsula (43% granite pebbles), at the western end of Toetoes Bay (30%) and west of Oreti Beach (24%). Allusion has already been made to the manner in which the area south-west of Bluff has been protected from incursions of greywacke and argillite pebbles by the rocky barrier of the Peninsula itself, and this doubtless explains the higher proportions of granite pebbles at that locality. The region at the western end of Toetoes Bay, where granite pebbles again become abundant, lies between the Oreti-Bluff and Mataura drainage systems, and presumably for this reason has to some extent escaped the debouchment of greywacke and argillite pebbles from the north. Similarly perhaps, the tongue of granite-rich gravels west of Oreti Beach has been preserved because of its position between the Oreti and Aparima estuaries.

The granite-pebble distribution, over the northern part of the Strait at least, thus does not represent a primary dispersal pattern as in the case of the greywacke - argillite assemblage, but is more in the nature of a palimpsest pattern partly obscured by the superimposed distribution of greywacke and argillite. Although at first glance such a hypothesis implies an earlier age for the granite distribution pattern, the relationship between the two patterns can be ascribed to a southward progressing "facies" change and it does not necessarily follow that individual granite pebbles are older than those of the greywacke assemblage.

An apparently anomalous feature of the pebble distributions in Foveaux Strait is the overall numerical inferiority and irregular distribution of the granite pebbles as compared with those of the greywacke assemblage, despite the fact that the Strait is dominated topographically by the mountainous granite massif of Stewart Island. The reason for this anomaly surely lies in the disparity in area between the catchments to the north and south of the Strait. While the ancient rivers entering the region of the Strait from Stewart Island could have drawn their waters from only a restricted area, the ancestors of the Oreti, Mataura and Aparima drainage systems were able to tap a vast expanse of the southern part of the South Island. Thus the volume of water available to transport the granite pebbles northward from Stewart Island was insufficient to compete with the rivers pouring other types of pebbles into the region from the north.

Nevertheless, the presence of appreciable quantities of south-derived granite pebbles in the submarine gravels in the north of the Strait, and even in some terrestrial gravels of Southland, suggests that the ancient rivers from Stewart Island did at one stage extend right across the region now occupied by the Strait. Subsequently, however, the northern drainage gradually extended southward, spreading vast quantities of greywacke and other pebbles that diluted the granitic pebbles and obscured their distribution pattern, and possibly even transporting some of the granitic pebbles southward again towards their source. Thus while virtually no granitic pebbles are found in Holocene gravels at Waituna Lagoon, their proportion in the older, Pleistocene gravels near Invercargill reaches 35%.

Prior to the final submergence of the Foveaux Strait region, the confluence of drainage systems from Southland and Stewart Island (with the possible exception of the Paterson Inlet drainage) lay approximately along a line extending north-west from the Lachlan Shoals. The distribution patterns shows that this line constitutes a crude boundary between gravels in which granite pebbles predominate, and those in which the greywacke assemblage is more important. It is significant that this same line coincides, both in position and trend, with the submarine valley—the Rakiura Gap—that lies between the Lachlan Shoals and the Fancy Group. It is thought that this valley represents a remnant of the channel by which the rivers converging upon the Strait, immediately before its submergence, finally made their way to the sea.

(c) *The porphyrite - diorite assemblage*

The distribution pattern of the porphyrite - diorite assemblage (fig. 15) is considerably less distinct than those patterns already described. Its most outstanding feature is the consistently poor representation of the assemblage throughout the Strait.

The highest proportions of porphyrite and diorite pebbles occur in the gravels of the western sector of the Strait, especially in the region between the northern tip of Stewart Island and Oreti Beach. A maximum value of 28% has been found at Sta. B 229, a few miles off Black Rock Point, Stewart Island, while blocks and angular fragments of diorite and gabbro dredged from the vicinity of the neighbouring Bishop and Clerk Is (Sta. B 233) suggest local derivation in this region

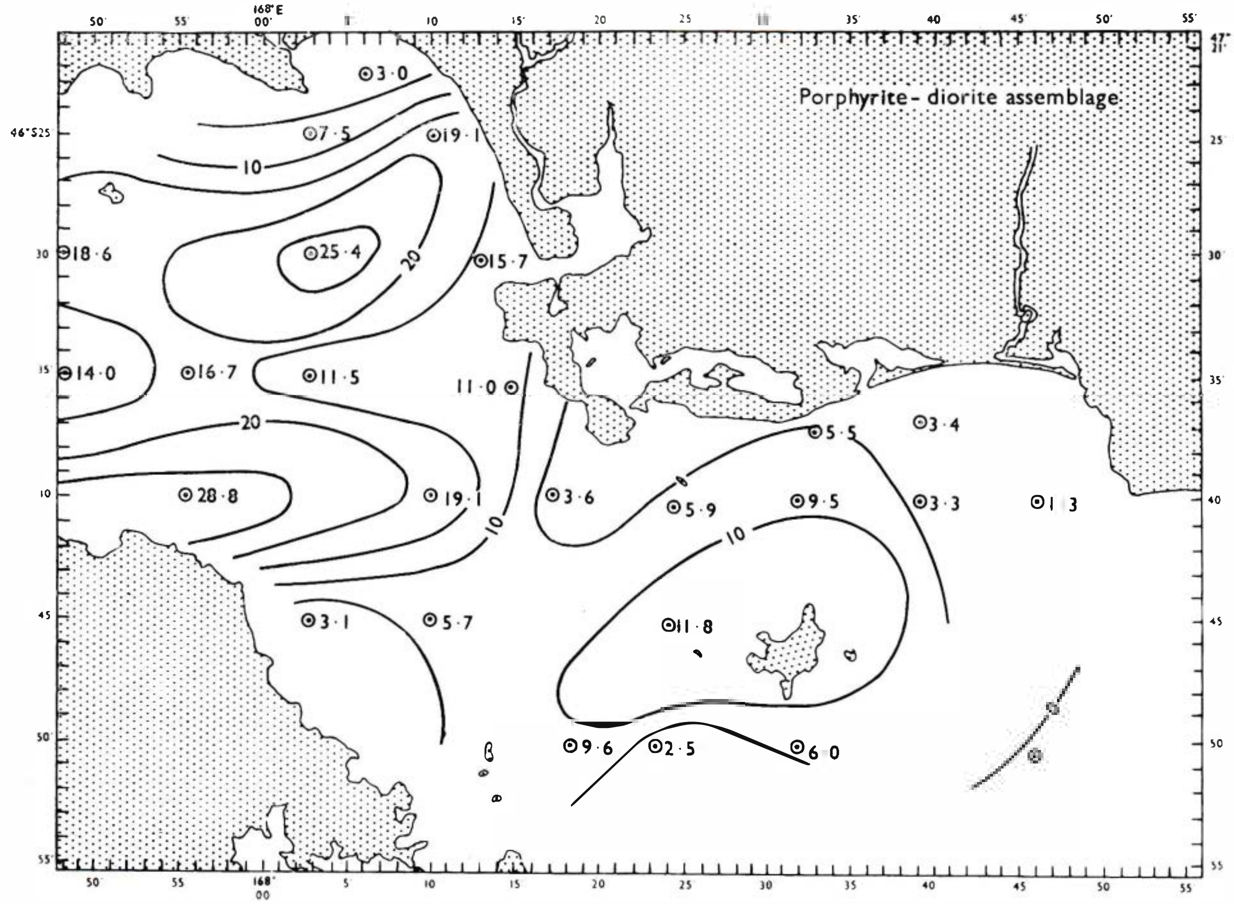


FIG. 15 Distribution of the porphyrite—diorite assemblage. Isopleths based on the percentages of total number of pebbles at each station, and interpolated at 5% intervals.

—either from the islands themselves or from the geologically little-known northern tip of Stewart Island.

The only other station (B 247) at which porphyrite and diorite pebbles exceed 20% lies in mid-Strait, to the west of the Oreti estuary. Shoals and reefs, probably denoting submarine outcrops of porphyrite and/or diorite, occur to the west, east and south, and may account for the comparative abundance of pebbles of these rock types at this station.

Eastward, the proportions of porphyrite and diorite pebbles in the gravels decrease, and very low values are found in Toetoes Bay and along the north-east coast of Stewart Island. Although somewhat higher values prevail around Ruapuke I, the assemblage is completely absent from the gravels at Sta. B 267, a few miles further to the east.

In contrast to the distribution patterns of the greywacke - argillite and granite - gneiss assemblages, the porphyrite - diorite distribution appears to bear little or no relation to either the Foveaux Strait coastlines or the rivers that enter the Strait. Such concentrations of the assemblage as do exist tend to be "insular" and associated with islands, reefs, shoals and submarine rock outcrops, from which the pebbles have in all probability been derived.

The directions of transport of the porphyrite and diorite pebbles, as inferred from their distribution pattern, show no evidence of the pronounced northward and southward trends so characteristic of the granite and greywacke distributions. On the contrary, east-west dispersal, approximately parallel to the trend of present-day tidal streams in the Strait, is more typical of the predominantly small-sized pebbles of the porphyrite - diorite assemblage. Whether the dispersal pattern is, in fact, primarily an effect of the recent marine environment or whether in common with other assemblages it retains basic features imposed by an ancient terrestrial drainage system, cannot be satisfactorily decided with the information available.

The abnormally low percentages of porphyrite and diorite pebbles in the Foveaux Strait gravels provide an even greater anomaly than that already discussed in describing the granite - gneiss assemblage. Taking into consideration the extent of outcrops of rocks belonging to the porphyrite - diorite assemblage along considerable stretches of the north shore of the Strait and on several of the larger islands, it becomes clear that the overall representation of the assemblage in the gravels is not in proportion to the abundance and proximity of these outcrops.

The paucity of porphyrite - diorite pebbles in the gravels can be explained on the basis that the regions now occupied by Foveaux Strait had already been drastically reduced by sub-aerial erosion prior to the deposition of the Holocene and Pleistocene gravels. Even at that early stage, the source rocks of the assemblage must have been deeply denuded to form more or less isolated hills and ridges at the sites of the present Ruapuke I., Bluff Peninsula and Longwood Range. During the ensuing aggradational phases, which followed the more pronounced lowerings of sea level, the gravels pouring into the region from the north and south would have completely buried the smaller rock masses and encircled the larger up-standing masses. Under these circumstances, local drainage from the latter would have been inadequate to contribute significant quantities of porphyrite and diorite pebbles to the gravels accumulating on the developing alluvial plain. However, during the final marine inundation of the Strait, additional porphyrite and diorite pebbles may have become incorporated in the gravels locally, as a result of coastal erosion by the advancing sea.

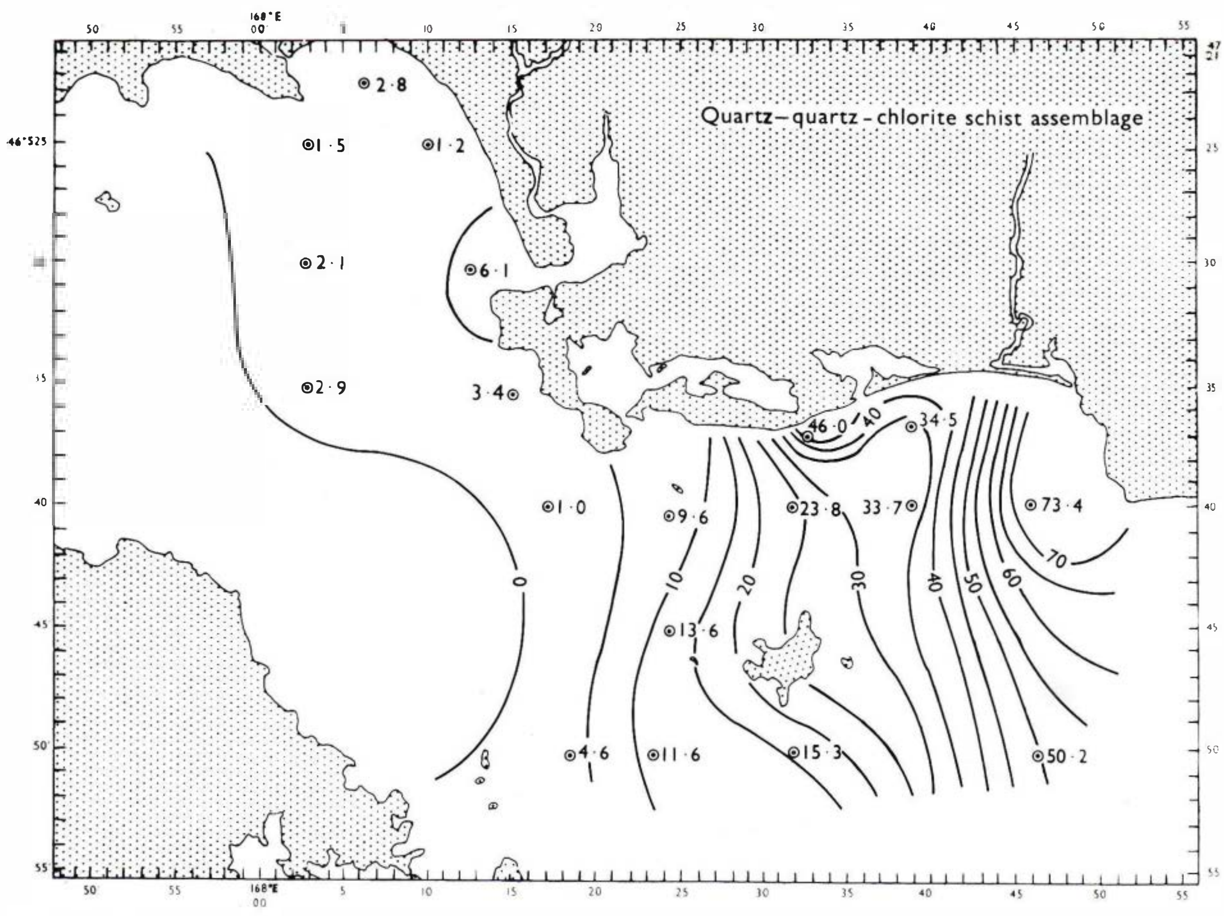


FIG. 16 Distribution of the quartz – quartz-chlorite schist assemblage. Isopeths based on the percentages of total number of pebbles at each station, and interpolated at 5% intervals.

(d) *The quartz - quartz-chlorite schist assemblage*

The distribution of the quartz - quartz-chlorite schist assemblage (fig. 16) is far simpler and hence more easily interpreted than the dispersal patterns already described.

From a maximum of 73% at the eastern end of Toetoes Bay (Sta. B 257) the proportions of quartz and quartz-chlorite schist pebbles decrease steadily southward and westward, the decrease being initially more rapid in the latter direction. A localised departure from this pattern is evident near the entrance to Waituna Lagoon, where values rise to 46% at Sta. B 254, and a small increase in the proportion of quartz pebbles is discernible off the Oreti estuary. To the west of a line bisecting the Strait between Centre I. and Lachlan Shoals, pebbles of the assemblage are virtually absent from the gravels.

Although in the eastern part of the Strait the dispersal pattern is incomplete because of the lack of gravel samples from the region east of Waipapa Point, the concentration of the quartz and quartz-chlorite schist pebbles around the mouth of the Mataura River is unmistakable. A predominantly southward direction of transport for the quartz and quartz-chlorite schist pebbles, normal to the modern current trends in the Strait, is equally clear, and the combination of these two features suggests a non-marine origin for the assemblage. Some local redistribution of the smaller pebbles by recent marine agencies is, of course, indisputable, and transport by contemporary longshore currents may be the explanation of the local concentration of quartz and quartz-chlorite schist pebbles at the western end of Toetoes Bay. This would, however, imply transportation counter to the known mean current trend in the northern part of the Strait.

By analogy with the greywacke - argillite - breccia assemblage, the quartz and quartz-chlorite schist pebbles are regarded as having been deposited before the final submergence of the region, the majority of them by a precursor of the Mataura River, which flowed southward to build up an alluvial plain on the site of the eastern part of Foveaux Strait. It is noteworthy that white quartz pebbles are common in Pleistocene and Tertiary gravels of Southland (Macpherson, 1937) and it may be that their sedimentary history is a long one.

SOME SEDIMENTOLOGICAL IMPLICATIONS OF THE PEBBLE DISTRIBUTIONS

Two somewhat unexpected features of sedimentation in Foveaux Strait are revealed by the distribution patterns of the four pebble assemblages.

(a) *Relationship between results of petrographic and grain-size analyses*

Plots of petrographic analyses of the gravels indicate relatively minor disturbance of the primary fluviatile dispersal patterns in the modern marine environment, despite the existence within the Strait of strong local currents. Although the effects of east-west tidal streams can be detected as subsidiary latitudinal distensions in the patterns (particularly in the narrow neck between Bluff and Saddle Point), and although a more intensive survey would doubtless reveal additional evidence of such distortion, nevertheless the palimpsest primary dispersal patterns remain readily discernible.

Since wholesale and indiscriminate transportation of pebbles within the Strait seems not to have occurred, it is suggested that the southward decrease in pebble size observed in the submarine gravels should also be regarded as a relict primary characteristic of the sediments. Significantly, a comparable north-south size gradation of pebbles can be recognised among terrace gravels over parts of the Southland Plain. The Brydone Gravels at Wyndham and the Kamahi Gravels near Makarewa (Willett, 1948), for example, contain more large-sized pebbles than gravels exposed further south at Gorge Road and Waituna Lagoon (table 2).

Such corresponding variations in particle-size composition suggest a common transporting agent for the submarine and terrestrial gravels, and lend additional support to the earlier contention of a fluviatile origin for the gravels now forming the floor of the Strait.

TABLE 2 Comparison of particle-size analyses of terrace gravels from the Southland Plain

	+64 mm	+32 mm	+16 mm	+8 mm
Wyndham	9.05%	26.55%	14.24%	15.96%
Makarewa	—	25.32	27.77	18.93
Gorge Road	—	2.23	12.73	26.95
Waituna	—	—	15.85	26.58

(b) *Relationships between the pebble distributions and the location of exposed source rocks in and adjacent to the Strait*

The second unexpected feature of the submarine gravels of Foveaux Strait is the absence of a broad correlation between the proportions of the four pebble assemblages and the proximity, extent and topographic prominence of outcrops of source rocks within and bordering the Strait. As already described pebbles of porphyrite and diorite occur in almost negligible quantities in the submarine gravels, despite the extensive and prominent exposures of identical rocks on both sides of the Strait and upon several of the islands within it. Similarly, the overall numerical inferiority of granite pebbles with respect to those of the greywacke assemblage is in complete contrast with the topographic domination of the Strait by the mountainous granite massif of Stewart Island

A feasible explanation of these phenomena rests upon the assumption that the main factor controlling the proportions of the different assemblages in the submarine gravels was the relative size (and hence the transporting power) of the ancient rivers that carried the pebbles to the site of Foveaux Strait. The rivers descending from the mountainous terrain to the south, while vigorous, would not have contained a great volume of water since their catchment area was restricted. Their capacity for transporting pebbles was thus limited, and became more so as the topography of the region was progressively reduced by erosion. On the other hand, the rivers from the north drew their waters from a vast area that extended over most of Southland, and their volume was sufficient to distribute the north-derived pebbles eventually throughout the entire Strait. As already seen, the source rocks of the porphyrite - diorite assemblage cropped out as mere isolated hills and ridges (with negligible run-off of their own) at the onset of the aggradational phase, and were incapable of contributing appreciable quantities of pebbles to the gravels. The importance of size of catchment area and amount of fluviatile run-off in the distribution of pebbles in Foveaux Strait has been discussed elsewhere (Cullen, 1966).

SUPPLEMENTARY DATA ON SUBMARINE GEOLOGY OF FOVEAUX STRAIT

ABNORMAL MAGNETIC VARIATION IN FOVEAUX STRAIT

Local magnetic anomalies are known to exist in Foveaux Strait (The New Zealand Pilot, 1958, p. 393). In an attempt to discover whether the incidence of these anomalies is related to the distribution of particular types of rock detritus in the sediments, magnetic susceptibility measurements have been obtained for samples from each of the main pebble assemblages. The measurements, made available by Dr T. Hatherton and Mr A. E. Leopard (Geophysics Division, New Zealand D.S.I.R.), are given in table 3

Typical quartz, greywacke and granite pebbles have low susceptibility values, for the most part less than 100 c.g.s. units/cm^3 $\times$ 10^{-6}, and even in extreme cases not exceeding 2,000 c.g.s. units/cm^3 $\times$ 10^{-6}. The susceptibilities of rocks ascribed to the porphyrite - diorite assemblage, on the other hand, range (with only one or two exceptions) from 2,000–22,000 c.g.s. units/cm^3 $\times$ 10^{-6}. and apparently average from 4,000–7,000 c.g.s. units/cm^3 $\times$ 10^{-6}.

Thus it would seem that only pebbles belonging to the porphyrite - diorite assemblage possess magnetic susceptibilities sufficiently high to have a potential effect upon the local magnetic field in Foveaux Strait. Numerically, however, porphyrite and diorite pebbles are poorly represented in the Strait, and only in two areas—off the northern extremity of Stewart Island and west of the Oreti estuary—do they occur in significant proportions in the gravels. In both of these areas the occurrence of subjacent porphyrite and diorite source rocks is suspected, and it would be impossible to distinguish between magnetic effects of the latter and of porphyrite and diorite pebbles in the sediments.

DEPOSITS OLDER THAN HOLOCENE BENEATH SURFACE SEDIMENTS IN FOVEAUX STRAIT

The lack of information concerning the thickness of sediments in Foveaux Strait that can be classed as Holocene has already been mentioned. There is a corresponding lack of knowledge of the

TABLE 3 Magnetic susceptibilities of characteristic pebbles from the submarine gravels of Foveaux Strait.

Assemblage	Petrographic identification	Magnetic susceptibility c.g.s. units/cm^3 x 10^{-6}	Remarks
Greywacke – argillite – breccia	Breccia	43	Contains fragments of dark argillite
	Greywacke	600	
Granite – gneiss	Leucogranite	72	
	Leucogranite	1,900	Abundant grains of opaque ore
	Gneissic biotite leucogranite	42	
	Granodiorite	*29*	
	Gneissic granodiorite	1,860	
Porphyrite – diorite	Porphyrite	1,360	
	"	4,500	
	"	3,250	
	Andesite	4,850	
	Diorite	2,760	
	Diorite	22,300	
	Diorite	6,450	
	Tonalite	6,500	
	Diorite-gneiss (?)	280	? granodioritic
Quartz – quartz-chlorite schist	Quartz	<1	

age, lithology and structure of the underlying formations, although it is possible to hazard opinions as to the continuity of certain of the Paleozoic rocks (for example, the Eglinton Volcanics and Longwood - Bluff Intrusives) at depth beneath the Strait.

Since Tertiary beds are known to occur beneath terrace gravels on the Southland Plain (Willett, 1948; Wood, 1958) and below Recent estuarine sands in Bluff Harbour (Wood, 1958), it is not improbable that Tertiary rocks are present also beneath the sediments flooring Foveaux Strait.

Couper (1951) has described the microflora of a sample of submarine lignite, dredged from a depth of 9 fm at lat. 46° 39.5′S, long. 168° 32′E, in Toetoes Bay, to which he assigned a Nukumaruan age—the Nukumaruan stage being at that time correlated with the Pliocene, but now regarded as Lower Pleistocene. Couper suggested that the sample may have been derived from a submarine lignite outcrop, and during the 1960 survey an attempt was made to confirm this. On that occasion, however, sand and gravel only were recovered from the site in Toetoes Bay (Sta. B 253).

During a visit to the eastern end of Waituna Lagoon in February 1961 the author noted a large, worn and rounded slab (more than 2 ft across and a foot thick) of brown, woody lignite, stranded above high-water level on the shingle spit. Palynological analysis by Dr W. F. Harris (N.Z. Geological Survey) shows this lignite to be younger than that examined by Couper, with a warm to temperate podocarp flora of probable post-glacial age, abounding in grains of manuka pollen. The provenance of this slab is unknown but, in view of its probable post-Flandrian age, it seems unlikely to have originated in a submarine outcrop. According to Tanner (1961) peat boulders are a normal product of erosion along the seaward margin of chenier plains, and local derivation from the low-lying northern coast of Foveaux Strait seems most credible for the Waituna lignite.

Discovery of the transported lignite slab at Waituna raises alternative possibilities concerning the provenance of the lignite described by Couper (1951). While the latter may well have formed part of a submarine outcrop in the Strait, as Couper suggests, it may equally well represent material eroded, transported and deposited either in the contemporary marine environment, or in a manner analogous to the Waituna sample during the Flandrian transgression.

NOTES ON PRE-QUATERNARY HISTORY

An account has been given of the submarine morphology and sediments of Foveaux Strait; some of the broader aspects of the history of the Strait, and the basic reasons for its existence may now be considered.

When discussing the provenance of the submarine gravels, it was suggested that the topography of the region now occupied by Foveaux Strait and the adjacent Southland Plain had already been severely reduced before deposition of the Quaternary gravels. The nature of near-horizontal Tertiary beds exposed on the Southland Plain provides evidence in support of this view, and Wood (1956, p. 86), describing exposures near Gore of Oligocene (Duntroonian-Waitakian) lignite measures with their marine and estuarine bands, states that they were "deposited in the course of one sedimentary cycle on an old land of very low relief". The wide extent of the marine transgression at this period is shown also by the occurrence of marine sediments of comparable age near Te Anau (Grindley, 1958, p. 50), far inland to the north-west of Foveaux Strait. Thus marine incursions over the southern part of the South Island, and presumably also over the region of Foveaux Strait, were possible by mid-Tertiary times.

The Strait lies along the southern flank of an extensive structural feature—the Southland Syncline—and its trend roughly parallels the regional strike of Paleozoic and Mesozoic formations on this flank. The development of the Strait is ascribed to lowering of the land surface by subaerial erosion during Cretaceous and early Tertiary times (when terrestrial conditions obtained throughout the area), initially perhaps along a line of weakness, either a poorly resistant formation or a major zone of strike faulting.

The temporary northward marine transgression during the Oligocene was followed by withdrawal of the sea, and a succession of relatively thin terrace gravels spread southward across the Southland Plain and Foveaux Strait regions throughout the remainder of Tertiary and Pleistocene times.

The Flandrian transgression resulted in the inundation of the low-lying southern reaches of these gravel spreads, leading, with subsequent modifications of coastlines and sea-floor, to the formation of Foveaux Strait as it exists today.

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APPENDIX

SEDIMENT SAMPLE ANALYSES

Abbreviations:
- G. L. O. - Large Orange-peel Grab
- D. D. - Devonport Dredge
- U. W. C. - Underwater Camera
- D. G. - Dietz Grab
- P. C. - 12-ft Piston Corer

Sample No	Depth (fm)	Latitude and Longitude	Gear	Total wt. of sample analysed (gm)	Component	Weight (in grams) of individual fractions +64	+32	+16	+8	+4	+2	+1.0	+0.5	+0.25	+0.125	+0.0625	-0.0625	Percentages of Pebble Assemblages Greywacke—argillite—breccia	Granite—gneiss	Porphrite	Quartz—Quartz-chlorite schist
B215	17	46° 50'S	GLO	620.3	Rock and mineral	-	-	-	66.1	173.2	79.8	40.3	4.7	18.7	101.9	2.9	0.2	41.7	36.9	6.0	15.3
		168° 31.5'E			Shell	-	-	-	4.2	14.4	13.3	16.3	6.9	36.2	39.9	0.8	0.5				
B216	12	46° 50'S 168° 23'E	DD		Sample unsuitable for analysis													45.3	40.6	2.5	11.6
B218	21	46° 50'S	GLO	179.7	Rock and mineral	-	-	-	-	-	-	0.1	0.1	7.9	60.3	14.6	7.4	-	-	-	-
		168° 09.8'E			Shell	-	-	-	-	0.7	0.6	1.3	4.4	23.5	33.4	12.5	12.9				
B219	20	46° 45'S	GLO	406.4	Rock and mineral	-	-	-	10.1	17.2	10.9	5.9	1 7	21.3	33.8	1.3	-	32.6	61.8	5.7	-
		168° 09.8'E			Shell	-	-	14.3	31.5	35.5	37.2	81.1	47.0	46.9	10.0	0.4	0.2				
B220	20	46° 40'S 168° 09.8'E	GLO		Sample unsuitable for analysis													48.2	32.7	19.1	-
B221	17	46° 40'S	GLO	488.4	Rock and mineral	-	-	-	62.0	54.9	24.0	11.1	9.1	91.8	17.3	1.8	-	63.6	31.8	3.6	1.0
		168° 16.8'E			Shell	-	-	-	19.0	18.1	28.1	59.3	49.5	37.0	4.1	1.1	-				
B222	15	46° 40.3'S	GLO	756.7	Rock and mineral	-	-	-	284.2	155.9	46.0	32.1	33.2	53.7	6.4	4.1	0.4	59.0	25.4	5.9	9.6
		168° 24.2'E			Shell	-	-	-	7.9	8.3	14.5	44.7	47.0	16.1	1.5	0.5	0.2				
B223	14	46° 45'S	GLO	629.3	Rock and mineral	-	-	-	94.4	82.5	26.0	14.7	16.3	74.7	25.7	3.5	0.1	48.0	26.6	11.8	13.6
		168° 24.2'E			Shell	-	-	7.0	26.0	25.5	23.9	74.9	65.4	58.5	8.4	1.5	0.3				
B224	17	46° 45'S	GLO	302.5	Rock and mineral	-	-	-	14.6	33.2	18.4	6.5	1.5	19.9	43.3	11.0	2.7	-	-	-	-
		168° 16.8'E			Shell	-	-	-	4.9	6.8	10.9	30.6	21.2	31.0	32.7	7.4	5.9				
B225	17	46° 50'S	GLO	851.0	Rock and mineral	-	238.5	186.5	128.5	91.4	30.0	11.0	1.9	35.9	32.3	1.3	0.1	55.8	30.0	9.6	4.6
		168° 18'E			Shell	-	-	-	7.0	5.1	5.4	15.0	11.3	34.1	14.6	0.7	0.4				
B226	27	46° 55'S	GLO	371.3	Rock and mineral	-	-	-	-	0.9	2.7	8.0	9.0	28.7	50.[illegible]	5.3	0.1	-	-	-	-
		168° 16.8'E			Shell	-	-	-	7.0	19.4	30.0	83.9	80.7	33.8	9.4	1.1	0.4				
B228	21	46° 45'S	GLO	623.6	Rock and mineral	-	-	-	6.5	8.4	16.2	33.8	17.8	98.2	40.6	4.1	0.1	28.7	68.2	3.1	-
		168° 04.5'E			Shell	-	-	4.5	18.1	17.5	38.0	196.5	62.4	50.9	8.1	1.6	0.3				

B229	15	46° 40'S	GLO	649.5	Rock and mineral	-	-	20.0	56.0	82.4	32.7	24.9	45.9	132.7	11.2	0.1	-	32.9	38.3	28.8	-
		167° 57'E			Shell	-	-	4.6	17.6	30.9	48.2	78.7	33.7	29.2	0.4	0.1	-				
B230	14	46° 40'S	GLO	420.0	Rock and mineral	-	-	-	-	0.4	1.2	1.4	7.5	45.4	46.5	19.2	13.5	-	-	-	-
		168° 04.5'E			Shell	-	-	-	11.6	6.4	5.9	13.0	42.3	96.9	47.6	16.4	44.8				
B231	12	46° 55'S	GLO	398.4	Rock and mineral	-	-	-	-	-	-	-	0.1	4.9	256.0	25.4	0.4	-	-	-	-
		168° 11.5'E			Shell	-	-	1.3	1.4	2.7	1.3	3.2	2.2	34.1	62.4	2.4	0.6				
B233	20	46° 39.7'S 167° 48'E	DD	-	Rock sample only													-	-	-	-
B234	26	46° 35'S	GLO	2948.5	Rock and mineral	-	104.0	484.3	1510.4	775.8	44.4	6.3	-	-	-	-	-	57.8	28.2	14.0	-
		167° 48'E			Shell	-	-	-	12.4	8.8	1.7	0.4	-	-	-	-	-				
B235	27	46° 35'S	GLO	635.8	Rock and mineral	-	121.3	80.2	115.5	70.5	18.5	4.7	0.9	2.4	8.8	1.5	0.1	46.0	37.3	16.7	-
		167° 55'E			Shell	-	9.8	22.3	46.5	33.0	30.8	47.3	10.5	7.2	3.3	0.7	0.2				
B236	20	46° 35'S 168° 02.5'E	DD	-	Sample unsuitable for analysis													48.0	37.6	11.5	2.9
B237	14	46° 35'S	GLO	501.7	Rock and mineral	-	-	-	8.2	5.8	0.6	0.2	1.4	31.5	96.6	36.6	30.8	-	-	-	-
		168° 11'E			Shell	-	9.2	14.2	43.3	47.5	34.5	15.0	16.2	50.4	33.4	7.9	18.4				
B238	18	46° 35.2'S	GLO	605.3	Rock and mineral	-	-	-	1.0	5.4	2.9	0.8	7.6	60.5	130.0	38.6	13.0	42.6	43.1	11.0	3.4
		168° 14'E			Shell	87.9	4.8	21.4	54.6	44.0	39.4	17.6	19.7	24.9	22.6	4.1	4.5				
B241	29	47° 00'S	GLO	467.7	Rock and mineral	-	-	-	-	-	-	0.1	1.0	18.3	193.3	31.9	0.2	-	-	-	-
		168° 16.8'E			Shell	-	-	-	0.9	1.2	2.3	12.8	13.0	85.9	101.7	4.6	0.4				
B242	45	47° 00'S	GLO	403.9	Rock and mineral	-	-	-	-	-	-	0.1	0.1	19.3	63.2	20.7	2.6	-	-	-	-
		168° 24.9'E			Shell	-	-	-	1.2	3.9	15.2	18.5	13.6	144.0	88.5	5.4	7.6				
B245	27	46° 30'S	GLO	2638.1	Rock and mineral	-	708.0	583.0	345.5	361.8	319.8	213.8	12.7	1.3	-	-	-	52.7	28.6	18.6	-
		167° 48'E			Shell	-	0.9	10.1	3.4	2.4	6.4	51.1	14.7	3.2	-	-	-				
B246	27	46° 30'S 167° 55.4'E	GLO		Sample unsuitable for analysis																
B247	20	46° 30'S	GLO	938.0	Rock and mineral	-	294.8	208.1	44.6	22..6	7.8	1.3	6.9	70.1	6.5	9.4	5.2	51.1	21.4	25.4	2.1
		168° 02.5'E			Shell	-	4.3	3.1	7.0	13.1	24.5	27.2	30.8	48.3	17.4	1.7	2.9				
B248	9	46° 25'S	GLO	960.2	Rock and mineral	-	162.2	217.6	221.2	79.7	26.3	31.0	13.7	44.3	39.9	30.3	2.8	65.6	24.5	7.5	1.5
		168° 02.5'E			Shell	-	-	-	8.2	8.7	8.9	17.7	8.4	23.0	12.3	3.0	1.0				
B249	10	46° 25'S 167° 55.4'E	GLO		Sample unsuitable for analysis																
B250	6	46° 22.5'S	GLO	1037.6	Rock and mineral	-	432.3	133.3	131.3	150.1	82.5	46.0	8.0	4.3	3.3	13.7	1.2	76.6	16.6	3.0	2.8
		168° 06'E			Shell	-	0.5	0.5	3.0	4.7	6.3	10.8	1.5	0.7	1.8	1.4	0.4				

APPENDIX (continued)

SEDIMENT SAMPLE ANALYSES

Abbreviations:
G. L. O. - Large Orange-peel Grab
D. D. - Devonport Dredge
U. W. C. - Underwater Camera
D. G. - Dietz Grab
P. C. - 12-ft Piston Corer

Sample No	Depth (fm)	Latitude and Longitude	Gear	Total wt. of sample analysed (gm)	Weight (in grams) of individual fractions													Percentages of Pebble Assemblages			
					Component	+64	+32	+16	+8	+4	+2	+1.0	+0.5	+0.25	+0.125	+0.0625	-0.0625	Greywacke -argillite -breccia	Granite -gneiss	Porphrite	Quartz Quartz-chlorite schist
B251	8	46° 25'S	GLO	983.1	Rock and mineral	-	100.1	205.3	245.9	50.5	12.1	46.8	69.4	25.4	7.4	27.8	0.8	55.8	24.0	19.1	1.2
		168° 10'E			Shell	-	-	-	9.4	29.9	36.7	86.2	22.1	3.1	1.7	2.3	0.2				
B252	10	46° 30.6'S	GLO	742.3	Rock and mineral	-	-	214.6	65.8	6.0	1.8	1.2	11.1	27.2	275.4	52.9	1.8	68.9	9.3	15.7	6.1
		168° 11.6'E			Shell	-	-	-	1.7	3.3	2.0	5.4	6.1	8.4	54.6	2.8	0.2				
B253	9	46° 40'S	GLO	627.3	Rock and mineral	-	-	-	153.6	71.7	30.0	14.8	40.7	78.6	8.9	3.3	0.3	41.7	25.1	9.5	23.8
		168° 31.4'E			Shell	-	-	3.2	29.5	30.1	19.1	62.4	59.5	19.1	1.6	0.5	0.1				
B254	8	46° 37'S	GLO	890.9	Rock and mineral	-	-	20.7	79.7	73.9	46.2	13.3	49.3	175.7	86.7	43.8	12.9	32.9	15.5	5.5	46.0
		168° 32.2'E			Shell	-	-	0.1	16.0	16.8	43.5	73.8	64.4	46.9	9.4	4.0	13.8				
B255	7	46° 36.7'S	GLO	909.7	Rock and mineral	-	363.3	82.8	101.0	80.9	43.8	37.6	20.6	7.3	2.2	1.1)	0.1	32.0	30.1	3.4	34.5
		168° 38.3'E			Shell	-	-	-	4.3	15.6	25.6	84.4	33.6	4.5	0.8	0.2)					
B256	12	46° 36.7'S	GLO	339.3	Rock and mineral	-	-	-	-	-	-	-	0.1	29.7	169.9	80.4	2.6	-	-	-	-
		168° 45.3'E			Shell	-	-	-	-	-	-	0.1	0.2	6.0	45.1	4.8	0.4				
B257	17	46° 40'S	GLO	880.1	Rock and mineral	-	-	104.9	107.3	88.5	66.9	102.2	62.6	45.0	25.7	8.8	0.3	11.9	13.5	1.3	73.4
		168° 45.3'E			Shell	-	-	31.7	55.6	54.9	27.8	38.0	25.4	19.9	12.1	2.2	0.3				
B258	10	46° 40'S	GLO	854.3	Rock and mineral	-	62.4	134.0	155.4	188.5	114.6	56.0	16.3	25.6	4.6	0.7)	0.1	34.4	28.6	3.3	33.7
		168° 38.3'E			Shell	-	-	2.9	12.2	17.1	13.4	17.6	17.9	12.3	2.4	0.3)					
B259	21	46° 45'S	GLO	317.0	Rock and mineral	-	-	-	-	-	-	-	0.3	0.9	177.0	114.6	2.9	-	-	-	-
		168° 45.8'E			Shell	-	-	-	-	1.3	2.2	4.3	1.7	1.0	6.1	2.4	2.3				
B260	14	46° 45.4'S 168° 39'E	GLO	-	Rock sample only													-	-	-	-
B261	29	46° 50'S	GLO	328.8	Rock and mineral	-	-	-	-	-	-	-	1.0	5.1	249.0	17.7	0.2	-	-	-	-
		168° 38.3'E			Shell	-	-	-	1.3	3.0	4.4	6.4	3.8	15.0	21.1	0.7	0.1				
B262	38	46° 52.05'S	GLO	490.1	Rock and mineral	-	-	-	-	-	0.6	3.2	13.8	71.8	82.6	46.5	11.3	-	-	-	-
		168° 31.3'E			Shell	-	-	1.3	7.8	20.7	54.6	61.9	26.7	40.1	33.9	9.9	3.4				
B263	29	46° 55'S	GLO	283.7	Rock and mineral	-	-	-	-	-	-	0.2	0.9	17.7	190.8	27.4	0.5	-	-	-	-
		168° 24'E			Shell	-	-	-	1.8	5.6	8.8	6.3	1.7	3.8	16.3	1.5	0.4				

B264	9	46° 39.5'S	DD	381.9	Rock and mineral	-	-	-	6.9	14.5	5.2	4.8	7.9	10.2	18.5	0.9	-	38.9	39.4	16.0	5.7
		168° 07'E			Shell	-	19.9	26.1	72.9	30.5	28.1	63.1	38.2	28.3	5.3	0.4	-				
B264a	-	46° 42.5'S	GLO	553.3	Rock and mineral	-	-	-	68.6	99.8	38.5	23.4	16.8	82.7	13.5	1.6	0.3	-	-	-	-
		168° 21'E (approx)			Shell	-	-	2.9	21.7	13.2	22.1	63.1	48.8	30.8	3.9	0.8	0.8				
B266	40	46° 55'S	GLO	292.2	Rock and mineral	-	-	-	-	-	-	-	0.5	4.1	232.4	18.0	0.3	-	-	-	-
		168° 31'E			Shell	-	-	-	0.4	1.9	3.5	9.8	3.9	6.5	9.5	1.2	0.2				
B267	39	46° 50'S	GLO	715.7	Rock and mineral	-	-	183.6	56.6	94.3	55.1	11.3	32.3	28.7	32.8	2.5	0.1	49.1	0.6	-	50.2
		168° 45.8'E			Shell	-	-	33.8	6.2	16.2	9.4	42.3	84.6	10.9	13.3	1.2	0.5				
B268	33	46° 45'S	GLO	213.9	Rock and mineral	-	-	-	-	-	0.1	0.2	1.8	8.1	134.6	15.9	0.2	-	-	-	-
		168° 52.8'E			Shell	-	-	-	0.6	1.8	5.2	10.5	6.3	6.8	20.9	0.8	0.1				
B269	38	46° 45'S	GLO	244.8	Rock and mineral	-	-	-	-	-	-	-	0.8	4.4	186.4	23.8	0.2	-	-	-	-
		169° 00'E			Shell	-	-	-	0.7	0.6	3.5	7.0	3.3	4.6	8.7	0.7	0.1				
B270	18	46° 42'S	GLO	172.1	Rock and mineral	-	-	-	-	-	-	-	0.6	117.5	26.6	10.1	0.4	-	-	-	-
		169° 00'E			Shell	-	-	-	-	-	-	-	1.6	10.9	3.0	1.2	0.2				
B271	11	46° 41.5'S	GLO	310.4	Rock and mineral	-	-	-	1.5	0.7	0.2	7.1	16.1	12.5	2.4	1.8	0.2	-	-	-	-
		168° 52.8'E			Shell	-	-	6.0	6.5	15.2	31.4	143.7	56.0	8.2	0.6	0.2	0.1				
B272	11	46° 44'S	GLO	612.9	Rock and mineral	-	230.7	59.7	42.0	24.9	4.3	3.7	16.5	91.5	18.2	3.1	0.1	-	-	-	-
		168° 31.4'E			Shell	-	3.0	3.3	8.1	6.3	5.0	42.6	24.6	20.4	3.5	1.0	0.1				
B273	10	46° 30.6'S 168° 11.6'E		-		No core												-	-	-	-
B274	14	46° 35'S 168° 11'E	PC	-		3'0" core												-	-	-	-
B275	18	46° 35'S 168° 02.5'E	PC	-		1'3" core												-	-	-	-
B276	14	46° 40'S 168° 04.5'E	PC	-		2'6" core												-	-	-	-
B278	44	46° 55'S	GLO	267.4	Rock and mineral	-	-	-	-	-	-	-	1.1	56.3	179.1	7.7)		-	-	-	-
																)	0.1				
		168° 38.5'E			Shell	-	-	-	0.2	1.9	3.8	6.2	2.5	4.0	4.8	0.7)					
B283	56	47° 00.4'S 168° 32.5'E	DG	-		Sample unsuitable for analysis												-	-	-	-
B284	54	46° 55.6'S 168° 45.6'E	DG	-		Sample unsuitable for analysis												-	-	-	-
B352	18-19	46° 42.2'S 168° 11.5'E drifting to 46° 42.4'S 168° 09.9'E	UWC	-		Underwater photographs												-	-	-	-

INDEX

MEMOIRS OF THE NEW ZEALAND OCEANOGRAPHIC INSTITUTE

Memoir No.	*Year*	*Title*
[1]	1955	Bibliography of New Zealand Oceanographic Committee. *N.Z. Dep. scient. ind. Res. geophys. Mem. 4.*
[2]	1957	General Account of the Chatham Islands 1954 Expedition. Part 1. Knox. *Bull. N.Z. Dep. scient. ind. Res. 122.*
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