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by

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ABSTRACT

Four prominent sediment facies occupy a succession of shore-parallel belts across the South Otago continental shelf.

1. The *modern terrigenous sand facies* occurs as a seaward-thinning wedge of fine grey sand on the inner shelf. The main sediment source for this facies is the Haast Schist terrain of the Clutha and Taieri River catchments; minor sources are the plutonic and metamorphic rocks of the Foveaux Strait-Western Province source area, and the volcanic complex of the Otago Peninsula.
2. The middle shelf is mantled by mainly Clutha-derived, iron-stained quartz pebbles and granules of the *relict terrigenous gravel facies*. A relict interpretation is confirmed by the presence of relict molluscs, an association with drowned estuarine deposits, and the occurrence of large gravel ridges that are largely out of equilibrium with the modern currents.
3. The *relict/palimpsest sand facies* occurs on the middle to outer shelf and incorporates mainly quartz-rich, fine to medium sands of mixed Foveaux Strait-Western Province and Haast Schist origins.
4. Shell sand and gravel of the *biogenic sand/gravel facies* are most widespread on the outer shelf. Components are both relict, typified by the molluscs *Tawera, Antisolarium, Umbonium* and *Zeacolpus*, and modern, including well-developed but localised living molluscan and bryozoan faunas.

When local sea-level data are taken into account, the combined evidence shows that these sedimentary facies developed in response to a succession of still-stands during the post-glacial transgression, augmented and altered by the modern hydraulic regime. The last maximum lowering of sea level (c.18,000–20,000 years B.P.) is represented by a terrace with a veneer of relict sand and molluscan debris at −110 to −120 m. The next still-stand is represented by a sediment wedge at −75 m (c.15,000 years B.P.) which coincides with the relict sand facies. The shoreline again stabilised at −55 m (c.12,000 years B.P.) when the nearshore ridges of the relict terrigenous gravel facies developed in association with estuarine deposits and sand wedges. Regional evidence suggests that further still-stands may have occurred at −30 m and −12 m, but any evidence for this is concealed beneath the modern sand wedge. With the stabilisation of present sea level (c.6,500 years B.P.) modern sands were introduced to the shelf and dispersed north-eastwards by the combined influence of southerly swell, tides, Southland Current, and storm-induced motions. Much of this sand eventually accumulates on the north or lee side of the Otago Peninsula, where it forms an extensive sediment wedge and submarine spit. Modern mud depocentres occur in the relatively sheltered Molyneux and Blueskin embayments. Modern currents, probably aided by the earlier transgressing sea, have modified the relict seascape. The relict gravel ridges have been eroded locally and the resultant sediment transported north-eastwards. Unmixing of relict deposits has generated palimpsest terrigenous sand that, together with biogenic sand, moves along the shelf, in some instances as sand ribbons. Such active transport has resulted in the mixing and burial of facies.

Keywords: continental shelf, modern sediment, relict sediment, facies, sediment transport, submerged shorelines, shelf fauna, Holocene shelf history, South Otago, New Zealand.

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INTRODUCTION

It has been known since the pioneering study by Marshall (unpublished 1931 report to the Otago Harbour Board) that the Otago continental shelf encompasses extensive areas of coarse-grained sediment. More detailed information on the sedimentology of the shelf has appeared in a number of recent papers (Andrews 1973, 1979; Bardsley 1977; Carter and Ridgway 1974), but rather than clarifying the regional situation, these data have given rise to a dispute as to the relative importance of modern and relict processes in shaping the shelf (Schofield 1976, 1977; Cullen 1976; Andrews 1976; Probert 1977). The protagonists in this discussion have based their arguments primarily on bathymetry and surficial bottom samples. Such evidence is often ambiguous and, to be realistic, it is difficult to resolve the complex problems of shelf sedimentology without recourse to a far wider range of data, including side-scan sonographs, high resolution seismic records, bottom photographs, piston cores, and physical oceanographic measurements.

G.R.V. *Tangaroa* cruises 1063 (August 4–22, 1977), 1097 (August 14–September 4, 1979) and 1128 (December 7–21, 1981) were spent gathering sedimentologic and geophysical data from the eastern South Island continental margin (Figs 1, 2). During these cruises we collected:

1. 1500 line kilometres of high-resolution, continuous seismic profiles using an Edo-Western 3.5 kHz system augmented by an E.G. & G. "Uniboom";
2. 170 line kilometres of side-scan sonographs using a Klein model 400 system;
3. 18 cores with a modified 7.5 cm diameter Kullenberg piston corer;
4. 14 box cores with a modified Reineck box corer of box dimensions 30 × 22.5 × 43 cm (deep); and
5. Underwater photographs from six stations.

This information was supplemented by over 500 surficial sediment samples gleaned from the New Zealand Oceanographic Institute collection.

Selected samples were routinely analysed for grain size by standard sieve and pipette techniques (*see* Folk 1965), for $CaCO_3$ and heavy mineral contents, and for faunal components. Additional sedimentary information was taken from the literature.

These data form the basis for the delimitation of various sedimentary facies and for our preferred interpretation of the disputed sedimentary and bathymetric features of the South Otago shelf.

THE SHELF ENVIRONMENT

The sediment cover on the continental shelf is a response to a number of interrelated factors of which shelf morphology and bathymetry, the hydraulic regime, sediment supply, and the most recent major fluctuations of sea level, are of prime importance.

General Setting

The coastline bordering the South Otago shelf is undergoing active uplift (Wellman 1979) and is, therefore, cliffed throughout its length. Rivers emerge at the coast either along ancient and deep-seated structural features (Clutha River), or else have been superposed across the coastal ranges (Tokomairiro and Taieri Rivers). A further feature is the presence of three major embayments — Molyneux Bay, Taieri Bight, and Blueskin Bay — bounded respectively by the promontories of Nugget Point, Quoin Point, and the Otago Peninsula (Fig. 1).

The study area is contained between Nugget Point and Karitane (Fig. 1). Here the shelf averages 30 km in width, except off the Otago Peninsula where it is reduced to about 10 km in width. The outer edge of the shelf is deeply dissected by seven major and a number of minor submarine canyons which connect eastwards with the tributary channels of the Bounty Trough. The shelf break generally lies at depths of 150–125 m but may reach 105 m at the heads of submarine canyons. Seaward gradients on the shelf range from 1:30 off the Otago Peninsula to a more typical 1:200 over wide areas of the middle and outer shelf. These gentle slopes are interrupted by a variety of abrupt changes in gradient, some of which are interpreted as submergent post-glacial shorelines by Andrews (1973); others are seafloor rock outcrops or the seaward edge of the modern, nearshore sand wedge.

Several regionally important bathymetric features occur on the inner and middle shelf (Fig. 1). A conspicuous nearshore terrace, marking the seaward face of the modern sand wedge, extends across Molyneux Bay. Further north, in the deeper waters of the Taieri Bight, the Saunders Ridges comprise three subparallel features that rise about 10 m above the middle shelf

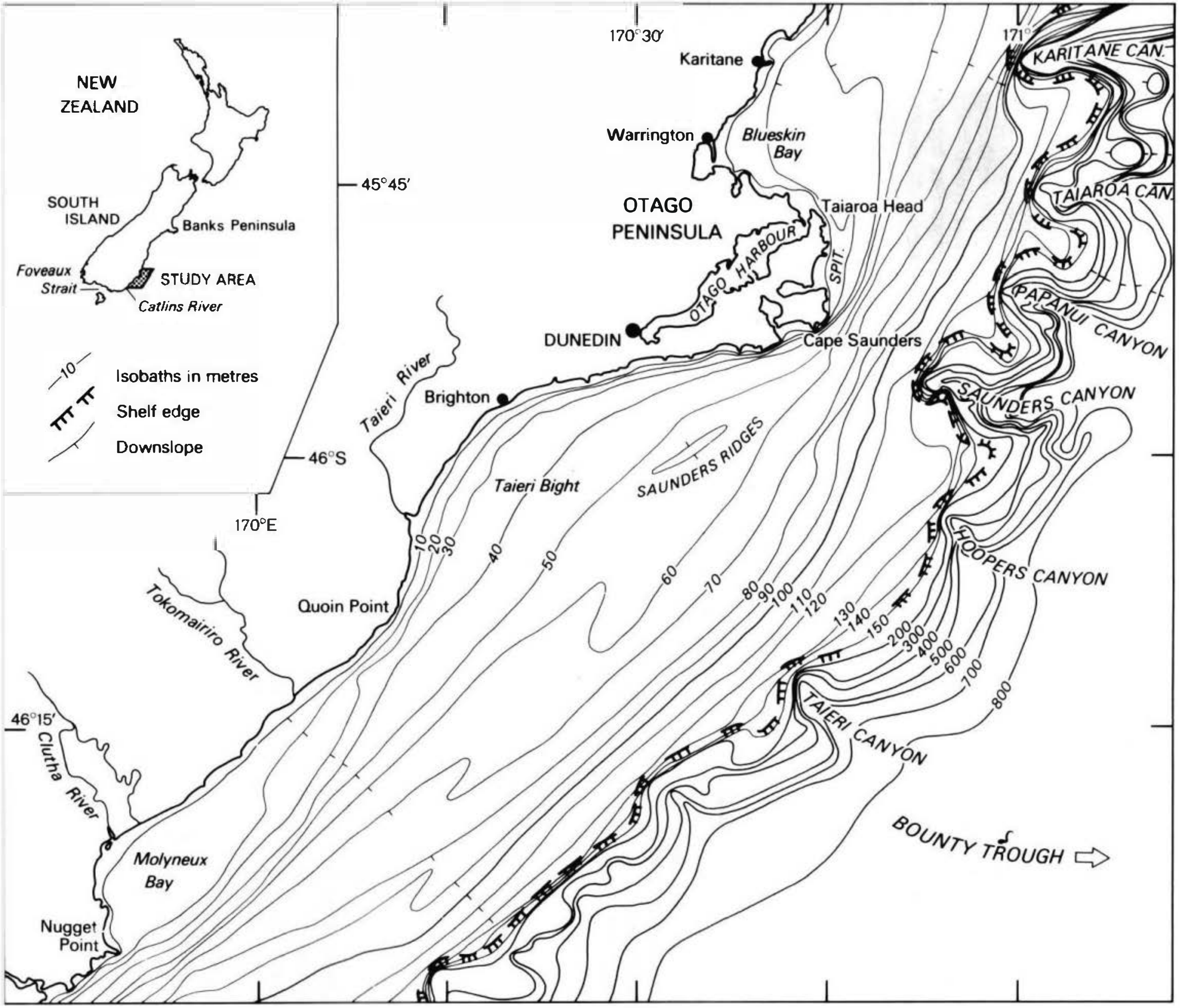


FIG. 1. Locality map and metric bathymetry for the South Otago continental shelf.

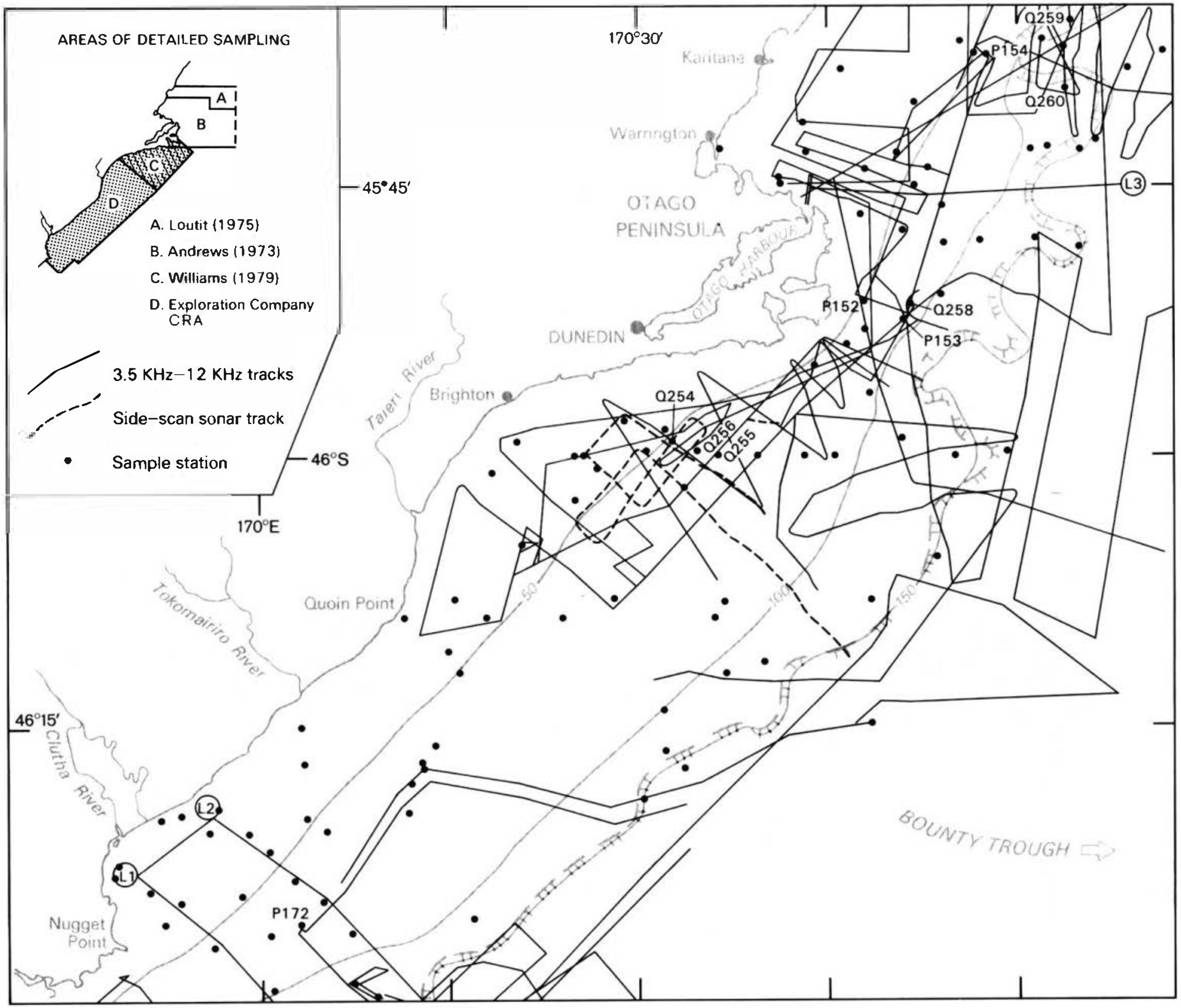


FIG. 2. Positions of high-resolution seismic, bathymetric, and side-scan sonar tracks, samples noted in the text, and areas of detailed sampling, i.e., one sample per $15\ \text{km}^2$ (inset), on the South Otago continental shelf.

with crests at depths of 48–55 m (Fig. 3). A third feature is a major submarine spit which runs due north for 25 km from the outer edge of the Otago Peninsula at Cape Saunders. We have informally named this feature the Peninsula Spit (Fig. 1).

Hydraulic Regime

A feature of the South Otago shelf hydraulic regime is the Southland Current, which transports warm, high salinity (> 34.5‰) oceanic water from the anticlockwise subtropical gyre in the Tasman Sea through Foveaux Strait and then north-east along the continental shelf and upper slope of the eastern South Island (Brodie 1960; Jillett 1969; Heath 1972c). Off Otago the current is centred approximately over the 100 m isobath during winter, the core moving inshore to lie near the 40 m isobath in summer (Jillett 1969). The inner margin of the Southland Current is demarcated across a sharp salinity and temperature front from a nearshore zone of neritic water whose physical properties vary widely with season and rainfall; the outer margin of the Current, against the less saline and colder Subantarctic Surface Water, usually lies near the shelf edge. Consequently, most of the shelf water column lies within the influence of the Southland Current.

Long-term measurements of current speed have yet to be made. We are therefore forced to rely on empirical calculations (Heath 1972c), scattered measurements using drifting devices (Heath 1973; Carter and Herzer 1979; Robertson 1980) and a short-term current meter record made 20 m below the surface (Robertson 1980). Bearing in mind the lack of precise measurement, the Southland Current apparently has a mean speed at the surface of around 7–15 cm s^{-1}. The mean speed near the seabed is considerably lower, between 2–6 cm s^{-1} judging by seabed drifter data (Carter and Herzer 1979) and short-term current meter measurements from 1 m above the seabed off Banks Peninsula (Heath 1976).

The local semi-diurnal tide has a range of 1.5 m. Off the Otago Peninsula the tidal flow is constricted and speeds at the surface reach 26 cm s^{-1} during the northward flood phase and the southward ebb phase (Hydrographic Office 1979). The time-averaged, mean tidal velocity is 1 cm s^{-1} at 70°T. On open sections of the shelf, such as to the south of the Otago Peninsula, the Hydrographic Branch (1952) report the "current and tidal streams are weak and depend upon wind drift".

A third element of the calm weather hydraulic regime is a persistent southerly "ground-swell" generated at distant storm centres in the Southern Ocean (*see*, e.g., Snodgrass *et al.* 1966; Pickrill and Mitchell 1979).

The prevailing strong winds and associated meteorological disturbances are from the south and southwest (de Lisle and Browne 1968; N.Z. Meteorological Service 1975–79). A prominent northerly wind component is also evident, but it is less intense than its southerly counterpart. One effect of the southerly gales and storms is to enhance the existing water motions, in particular, the Southland Current, flood tidal currents, and ground-swell. Storms also invoke other responses including wind-drift currents, barotropic and baroclinic currents (Carter and Herzer 1979), and undercurrents associated with upwelling and downwelling (Heath 1972a, b).

Sediment Transport

Beach studies (Marshall 1905, unpublished 1931 report to the Otago Harbour Board; Elliott 1958; Bardsley 1972, 1977), petrographic evaluation of shelf sediments (Andrews 1973, 1979; Williams 1979), and theoretical considerations based on physical oceanographic data (Carter and Heath 1975; Carter and Herzer 1979), all confirm a dominant north-eastward transport of sediment along the South Otago shelf.

As sediment transport is strongly influenced by the meteorology it is relevant to discuss calm and storm weather transport regimes. Under calm weather conditions, transport of bedload is liable to occur at three localities:

1. On the inner shelf, where the southerly ground-swell not only induces a north-eastward longshore drift in the surf zone (Hodgson 1966), but also stirs sediment down to water depths of about 30 m. This stirring renders bedload more susceptible to transport by available linear currents; in this case the tides and Southland Current.
2. On the middle to outer shelf off the Otago Peninsula, where sand is probably transported on a regular basis when the northwards flowing flood tide reinforces the Southland Current. Tidal speeds here are also enhanced by the constriction of the flow against the Peninsula. In contrast, on the open shelf neither the tides nor the Southland Current nor a combination of these motions have speeds above the threshold of fine sand movement — here taken as about 30 cm s^{-1} (Sternberg and McManus 1972).
3. At the shelf edge, where transport is likely to be instigated by internal waves. While evidence for such a process off Otago is circumstantial, the presence of (i) coarse, moderate to well-sorted sediment at the shelf edge; (ii) flows strong enough to transport sand in the Otago canyons (unpublished data, N.Z. Oceanographic Institute); and (iii) internal waves detected in echograms of the deep scattering layer (Carter and Herzer 1979; this study) collectively suggest this process may be significant.

The passage of meteorological disturbances markedly reinforces the calm weather regime to induce more widespread and intense transport over the shelf. Sediments on the inner shelf are probably in a constant state of motion under the combined influence of southerly swell, locally generated wind waves and wind-drift currents. The dominance of southerly storm-induced motions produces a north-easterly transport of sediment coupled with an onshore com-

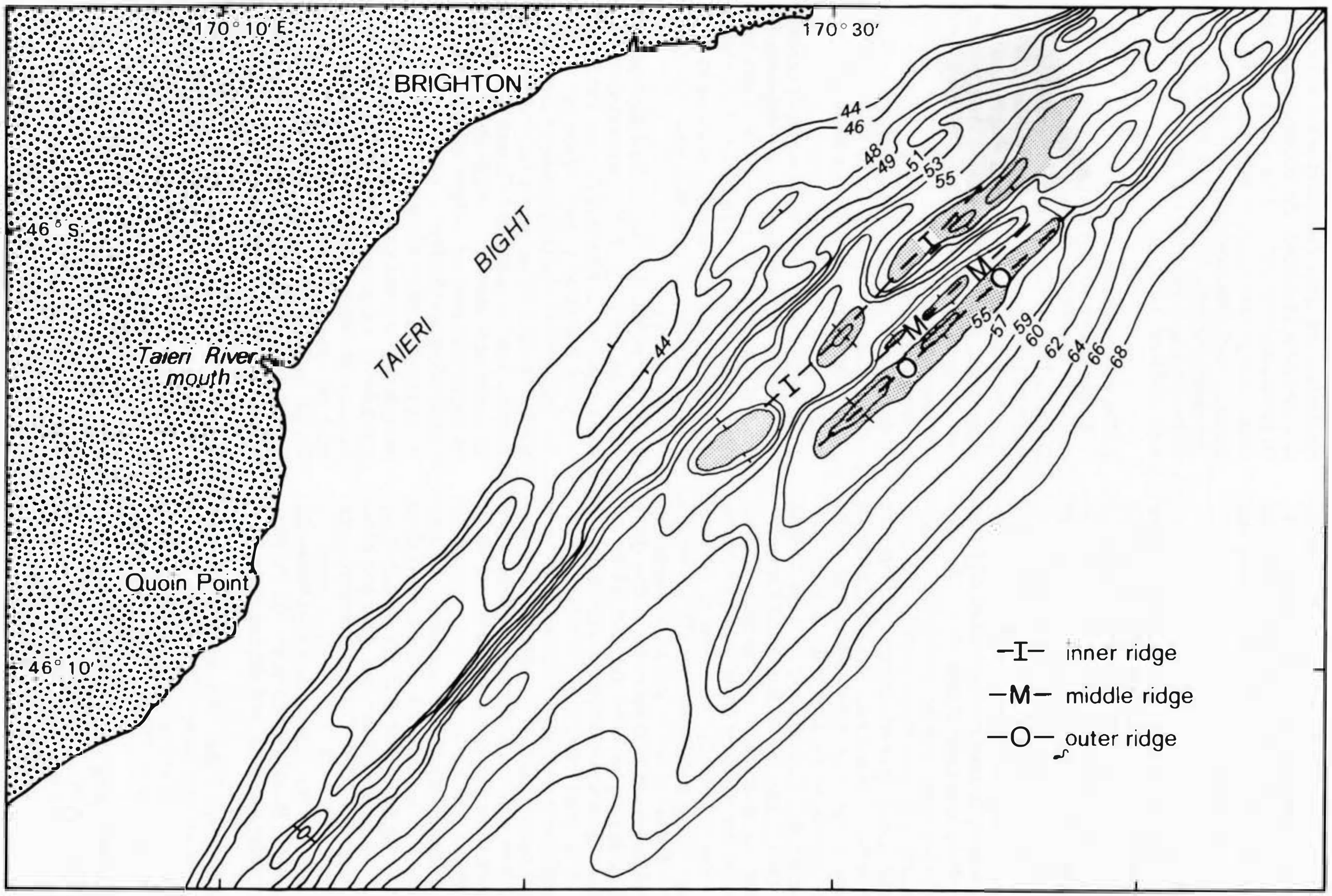


FIG. 3. Detailed metric bathymetry of the Saunders Ridges (stippled) drawn from soundings collected by the Hydrographic Office, Royal New Zealand Navy.

ponent due to Coriolis deflection of wind-drift currents. River sediment reaching the shelf is thus confined to a north-eastward travelling band along the inner shelf. In the southern corners of Molyneux and Blueskin Bays, the direction of inner shelf sand transport is locally reversed in response to anticlockwise gyres within the bays (Bardsley 1972; Carter and Heath 1975) and local north-east wind waves and drift.

Transport on the middle to outer shelf depends upon storm intensity and as a consequence is less frequent than transport in shallower reaches. All the previously mentioned motions play some role, and in particular large swell, which is probably effective in stirring sand down to water depths of over 100 m (Carter and Herzer 1979). In addition, storm-generated barotropic and baroclinic components may supplement the mean flow and tides to produce a force capable of transporting sand.

Sediment Supply

Terrigenous sediment reaching the South Otago shelf comes from rivers, erosion of the coast, and from the shelf south-west of Nugget Point. Of the fluviatile sources, the Clutha River is overwhelmingly dominant. It currently supplies about 1.6 million tonnes (Mt) of sediment per year (estimated from the data of Adams 1978). Prior to construction of the Roxburgh dam, which entraps 1.84 Mt y^{-1} (Thompson and Adams 1979), the Clutha delivered approximately twice as much sediment as at present. By comparison, the input from the Taieri River, the next biggest river on the coast, is only 0.53 Mt y^{-1} (Adams 1978).

The sediment contribution from coastal erosion is difficult to quantify from available data, but it is likely to be small as much of the coast is in an accretionary phase apart from erosion at the tip of the Otago Peninsula (Gibb 1978). South of Nugget Point, the Catlins coast is eroding (Gibb 1978) and the resultant sediment, together with the fluviatile input, is swept north-eastwards into the study area. As will be demonstrated in the following section, the southern sediment supply is significantly smaller than the Clutha input but is nevertheless locally prominent in sediment distribution patterns and heavy mineral suites, particularly on the middle and outer shelf.

The source areas yielding sediment to the South Otago shelf are varied and distinctive. At the south-western corner of the South Island, high-grade metamorphic and plutonic rocks of the Foveaux Strait-Western Province (Landis and Coombs 1967) yield a distinctive heavy mineral suite that has been traced in beach sediments to the Clutha River mouth (Martin and Long 1960; Bardsley 1977), and in shelf sediments to as far north as the Taieri Bight (Williams 1979).

Apart from volumetrically minor amounts of Cenozoic sediment, the remainder of the south-eastern South Island is underlain by rocks of the Rangitata Orogen. The Catlins district comprises easily weathered zeolite and chlorite-cemented volcanogenic sandstones and argillites of the Hokonui Assemblage. Heavy forest cover and high rainfall in the coastal catchments result in the Catlins rivers carrying little bedload; the sediment is mainly mud. What sand reaches the coast is quartz deficient with volcanogenic lithic grains prevailing, but it is seldom present in sufficient abundance to contribute markedly to local beach sands, which are dominated by the Foveaux Strait-Western Province plutonic mineral suite (Martin 1961).

North of Nugget Point the Clutha, Tokomairiro, and Taieri Rivers drain catchments developed within the Haast Schist. The derived sediment is enriched in quartz (Adams 1978) and mica but has few diagnostic heavy minerals (Bardsley 1977). Near the coast the rivers flow for a short distance through Caples metagreywacke thus introducing a volcanogenic lithic component to the fluviatile load.

Though no major rivers emerge at the coast in the vicinity of Dunedin, the lava flows of the Dunedin Volcanic Complex suffer direct marine erosion, as well as erosion by small streams. Accordingly, local beach sands contain an important component of volcanic detritus, including titanaugite, olivine and brown hornblende (Bardsley 1977) — the Dunedin volcanic mineral suite. Karitane marks the point at which the volcanic mineral suite is replaced by Haast Schist minerals, and is also the parting point between the anticlockwise Blueskin Bay current gyre and the main northward current flow over the shelf.

SEDIMENTARY FACIES

Shelf sediments off South Otago (Fig. 4), as elsewhere off the eastern South Island, are distributed as (i) an inner shelf belt of modern terrigenous sand; (ii) a middle shelf belt of relict terrigenous sand and gravel; and (iii) an outer shelf zone of biogenic sand and gravel (Andrews 1973; Carter 1975; Williams 1979). Such a distribution is of course generalised and subject to local variations, reflecting, for example, variability in the hydraulic regime and sediment supply.

Previous sediment studies of the South Otago shelf

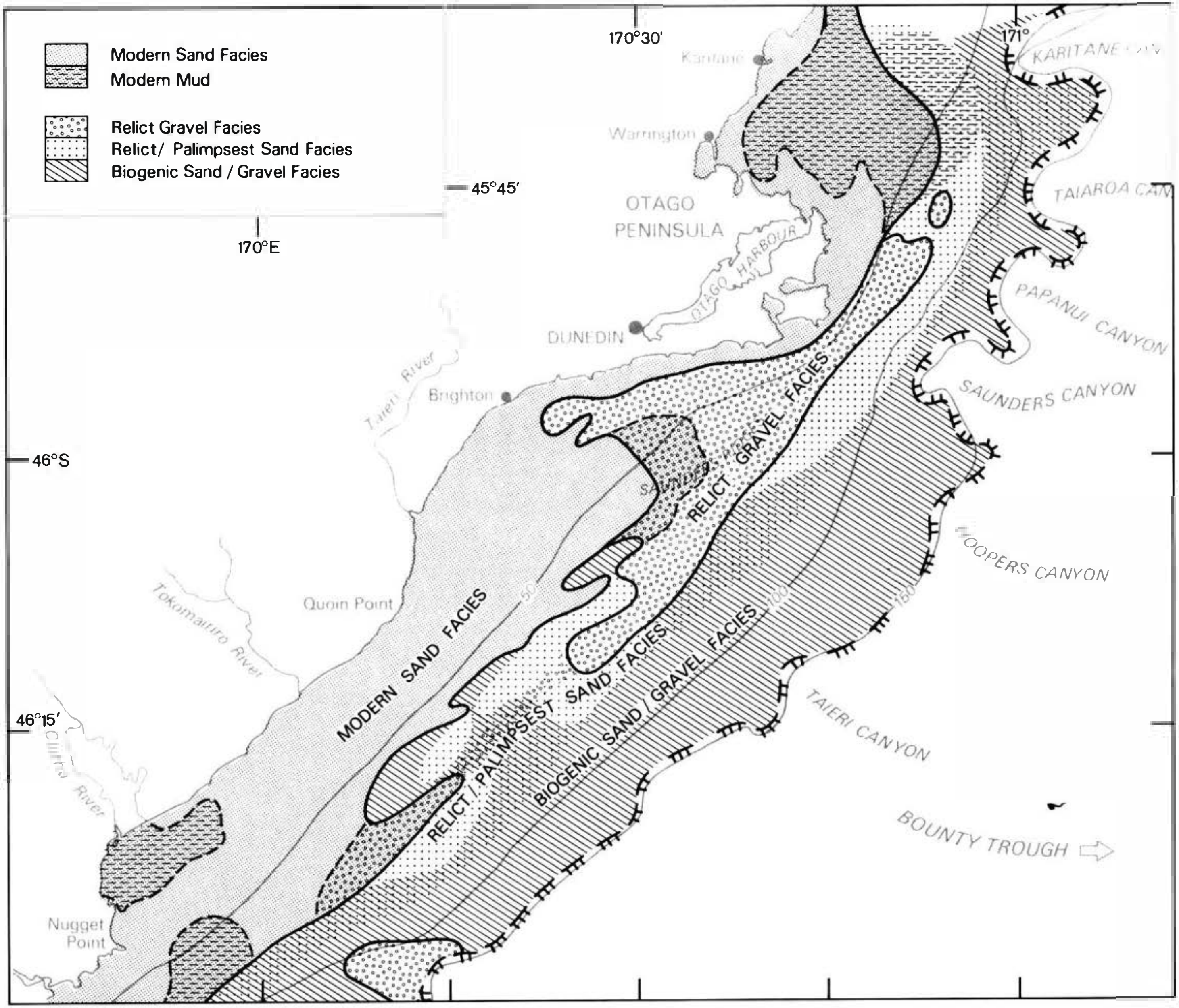


FIG. 4. Distribution of the main sediment facies on the South Otago continental shelf determined from all available sedimentary and geophysical data. Solid boundaries delimit main body of the facies, dashed boundaries denote areas where facies limits are indistinct, e.g., areas of sediment mixing.

have relied heavily on grain size data, e.g., Andrews (1973, 1979), Carter and Ridgway (1974). While such an approach can be of value, grain size data are open to interpretation, particularly when dealing with the complex polymodal sediments as exist off Otago (Schofield 1976). We prefer, therefore, to take a broader view of the sediments using morphologic, stratigraphic, compositional and faunal as well as textural evidence to produce a sediment facies map. Such a facies approach is, in our opinion, the soundest method on which to develop a sedimentary model for the post-glacial evolution of the continental shelf.

Modern terrigenous sand facies

Distribution

Since sea level stabilised some 6,500 years B.P. (Gibb 1979) sand derived from local rivers and south of Nugget Point has been contained within a nearshore belt (Fig. 4). The belt achieves its maximum width of 18 km off the Clutha River mouth, from where it narrows slightly to the north-east before widening to 17 km in the vicinity of the Taieri River mouth. As this broad belt of sand approaches the Otago Peninsula it narrows dramatically to a nearshore ribbon only 2–3 km wide, and, apart from the Peninsula Spit, the ebb-tidal delta system in the vicinity of the Otago Harbour entrance, and the wedge in Blueskin Bay, the width of this ribbon remains fairly constant to just north of Karitane.

The cause of the marked reduction in the width of the sand belt south of the Otago Peninsula cannot be pinpointed with certainty. Though it may simply reflect the maximum extent of modern sand transport along the middle shelf, we rather suspect that it marks a response to local hydraulic conditions, namely, a localised reversal of currents against the Peninsula.

Another feature of the sand belt is its lobate seaward margin with offshore relict sediments. Tongues of modern sand extend along the shelf to the north-east, thereby confirming the regional trend in sediment transport.

Petrography and Provenance

The sediment is typified by light olive-grey sand of mean grain size 2.1–3.5ϕ (fine to very fine) and standard deviations of 0.4–0.9ϕ (moderate to well-sorted) (Fig. 5, Table 1). Close inshore the sand has no discernible textural trend, but further seaward in depths of 30–35 m between Molyneux Bay and the Otago Peninsula, the sand becomes progressively finer grained to the north-east in accordance with regional dispersal trends. The rapid flow around the Peninsula produces a slight coarsening and an improvement in sorting (Andrews 1973). Further north again, in Blueskin Bay, there is a return to very fine sand (here diluted by the addition of a mud component). At the seaward feather edge of the sand belt increasing amounts of coarse biogenic debris occur, obscuring any intrinsic grain-size trends.

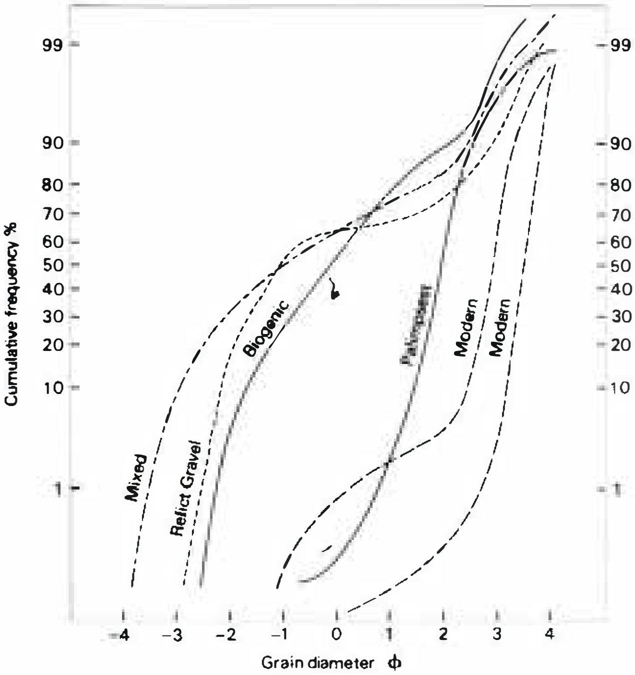


FIG. 5. Representative grain size distribution curves for sediments of the major facies on the South Otago continental shelf.

A low biogenic component, as reflected by $CaCO_3$ contents of 10–25%, is a feature of the facies, except towards the edge of the belt where increasing quantities of modern and relict shell debris raises carbonate contents to above 40% (Table 1).

With respect to terrigenous components, the beach sands of the Catlins coast are rich in minerals from the Foveaux Strait-Western Province, notably well-rounded, green hornblende and hypersthene (Martin 1961; Bardsley 1972, 1977). This sediment travels north-east up the coast and is dominant to just south of the Clutha River mouth. Here, in the space of a few kilometres, the beaches are overwhelmed by Haast Schist-derived quartzo-feldspathic sands with a prominent mica component and a heavy mineral suite dominated by garnet and epidote (Bardsley 1977; Williams 1979). This sharp change is probably the result of (i) the large influx of Clutha sediment relative to the Catlins input, and (ii) reduced transport of Catlins sand as it moves into Molyneux Bay, an embayment which receives some shelter from southerly swell and storms.

On the exposed continental shelf Foveaux Strait-Western Province sand has been transported along the seaward edge of the Clutha sediment wedge into the Taieri Bight. Here, in depths of 40–60 m, the sand forms a belt separated from the coast by a belt of Haast Schist sand. Though mixing of these two suites

TABLE 1: Characteristics of the major sedimentary facies on the South Otago continental shelf.

Facies	Depth range (m)	Estimated age (ky)	Maximum thickness (m)	Sediment type	Sediment components	Heavy minerals and provenance	CaCO$_3$ (%)	Key macrofauna
Modern Terrigenous Sand	0–70	0–6.5	9	fine–very fine grey sand	quartz feldspar mica	garnet epidote of Haast Schist; pyroxene olivine of Dunedin Volcanics; hornblende hypersthene garnet of Foveaux Strait-Western Province	10–40 $\bar{x}=18.2$	*Umbonium* *Antisolarium*
Relict Terrigenous Gravel	30–80	11–12	15	sandy, granule -pebble gravel	quartz, commonly iron-stained, + minor greywacke	Haast Schist + Foveaux Strait-Western Province minerals as above	10–50	*Tawera* *Zeacolpus* bryozoa actinarians ophiuroids
Relict Palimpsest Sand	30–120	11–20	10	fine–medium sand	quartz feldspar, commonly iron-stained	Haast Schist + Foveaux Strait-Western Province minerals as above	< 50 $\bar{x}=40.6$	mid-shelf *Tawera* *Zeacolpus* minute bivalves bryozoa outer shelf *Chlamys delicatula* *Fusitriton* *Tawera* *Zeacolpus* *Antisolarium* *Umbonium* minute bivalves
Biogenic Sand Gravel	50–120	0–20	probably a few metres	medium sand to sandy gravel	molluscs, bryozoa, foraminifera		50–75	as above

doubtless occurs in some places between Nugget Point and Brighton, and though the Foveaux Strait-Western Province sand may be totally buried by Haast Schist material in others, contrasted sand belts of plutonic and schist origin apparently persist as broadly separate features with distinctive heavy mineral suites, at least as far north as Brighton (Williams 1979). Beyond this point Haast Schist sand is dominant to the volcanic complex of the Otago Peninsula. Sand provenance remains essentially similar along the 65 km of coast between the Clutha River mouth and the Peninsula, the main change being a gradual increase in sediment maturity as feldspar is destroyed (Williams 1979).

A sharp change in provenance due to the incoming of pyroxenes and olivine from the Dunedin Volcanic Complex occurs some 15 km north-east of the first occurrence of volcanic outcrops at the Dunedin coast. Though the more south-westerly volcanic occurrences are largely non-porphyritic, and therefore do not easily yield sand-sized mineral grains, this distribution nonetheless serves to confirm that net longshore movement is to the north-east. Sands of the Peninsula Spit and the ebb-tidal delta at the Otago Harbour entrance are of mixed provenance, but are dominated by the Haast Schist mineral suite (Marshall, unpublished 1931 report to the Otago Harbour Board; Scott and Landis, unpublished 1978 report to Dunedin Metropolitan Planning Authority). Beaches bordering Blueskin Bay to Karitane are also dominated by Haast Schist sand with an admixture of volcanic material (Bardsley 1977; Landis, pers. obs.). Locally, as on Warrington Beach, grains of volcanic origin may achieve dominance. However, appreciable amounts of volcanic minerals have not been observed north of Karitane.

Structure and Stratigraphy

Seismic profiles show the modern terrigenous sand facies is part of a seaward thinning wedge of variable morphology and dimensions (Fig. 6). The wedge, believed to be a composite feature of earlier Holocene wedges, is most extensive and thickest (34 m maximum) beneath the almost flat floor of Molyneux Bay. Outside the bay the seabed slopes quickly to the middle shelf where the wedge thins to zero thickness some 18 km from shore (Fig. 6). That sediment thinning is coincident with the seaward limit of the bay suggests the seaward progradation of the Clutha wedge has been reduced or even checked by the hydraulic regime of the exposed shelf. Immediately seaward of the Clutha wedge, modern sand forms a thin drape over an older sediment wedge formed against a terrace level at 75 m depth (Fig. 6).

To the north-east, beyond the sheltered waters of Molyneux Bay, there is a marked reduction in the size of the sand wedge, presumably in response to increasing distance from the Clutha source and to greater exposure to southerly storm-induced motions. Even off the next prominent sediment source, the Taieri River, the wedge is only 8 m thick (maximum) and thins out just 7 km from shore. Further out to sea, additional deposits of sand, 6–8 m thick, have accumulated in depressions formed within the pre-modern substrate. However, the Taieri River is probably not the main source of these deposits as the Taieri wedge pinches out against a gentle rise located just landward of the deposits. More likely these offshore sands have been derived from the Clutha River and Catlins shelf; a contention that is supported by the heavy mineralogy (Williams 1979).

There is no seismic coverage of the nearshore sand wedge bordering the Otago Peninsula but available bathymetric data (unpublished information, N.Z. Hydrographic Service) suggest it is a simple, seaward tapering feature whose lateral continuity is broken by rocky promontories extending from the Peninsula. From Cape Saunders the wedge becomes the northward-tapering Peninsula Spit (discussed in the next section). In Blueskin Bay the sand forms a gently sloping, featureless deposit with its feather edge located at 75 m depth (Fig. 6). North of Warrington the inner shelf exhibits signs of sediment starvation. The nearshore sands are often thin, and pinch out against submarine Cenozoic rock outcrops or are confined to conduits between volcanic rock pinnacles (Fig. 7).

The modern terrigenous sand facies constitutes the youngest stratigraphic unit. Close to shore it commonly rests unconformably on gently seaward dipping sediments which, by inference from the land geology and a limited number of dredge hauls, are Cenozoic mudstones and sandstones. On the middle shelf the sand mantles relict deposits shown in cores to be iron-stained quartz gravel or, less commonly, biogenic gravel and sand (Fig. 8).

Peninsula Spit

Where the sediment transport system encounters a promontory a sand spit is formed along the shelf north of the promontory (*see*, e.g., Herzer 1981). A classic example is the submergent spit off the Otago Peninsula. It is 25 km long, tapering from 3–4 km in width where it attaches to the shoreface north of Cape Saunders, and fading out northwards on the middle shelf off Karitane (Fig. 9). The eastern side of the spit rises steadily to the crest at a depth of 20 m from a depth of 55 m on the middle shelf. The western edge, by comparison, has much less relief — about 4 m, except against a dredged channel to Otago Harbour, where it also forms part of the ebb-tide delta system of the harbour mouth. The southern parts of the spit comprise well-sorted sand grading to silty sand towards and beyond the northern extremities (Marshall, unpublished 1931 report to the Otago Harbour Board; Andrews 1973) where notable zones of mica-rich sand occur (Loutit 1975).

Inset 3

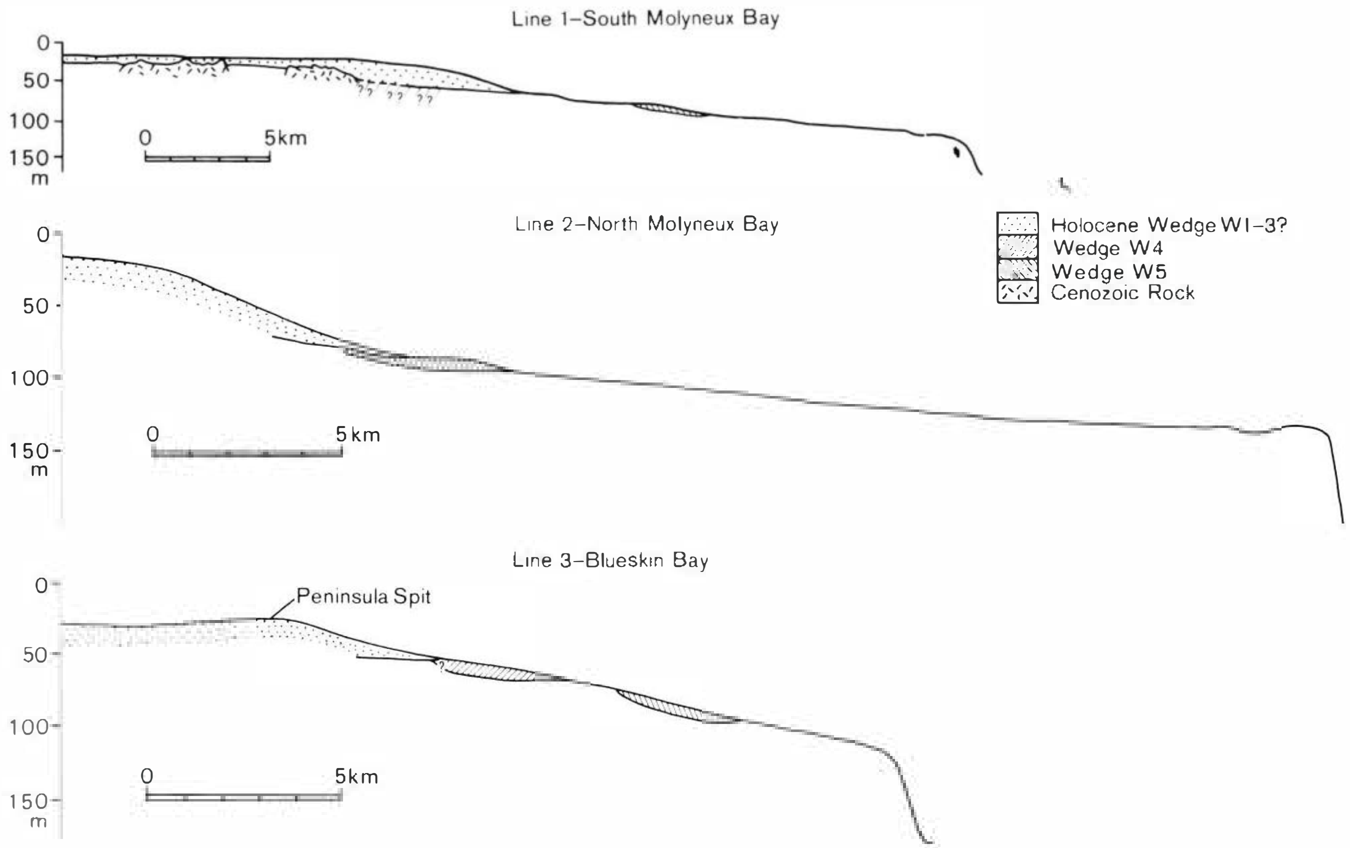


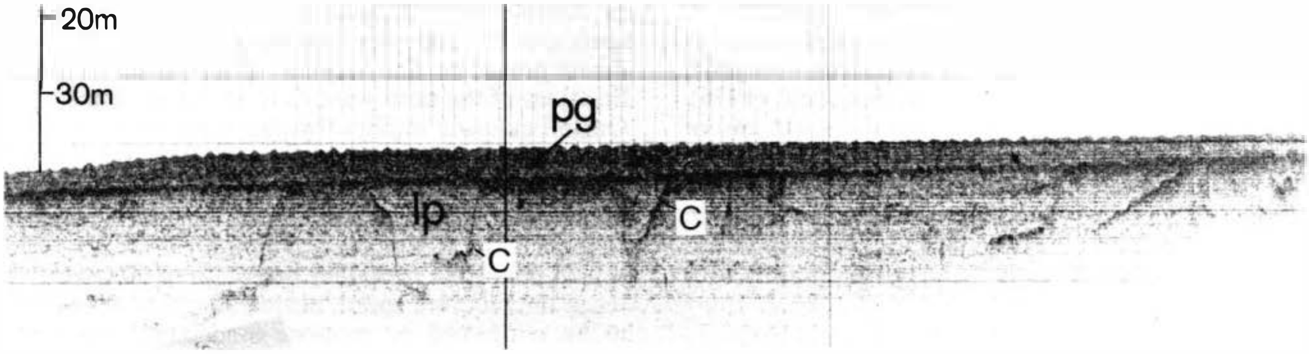
FIG. 6. Line interpretation of "Uniboom" seismic profiles in Molyneux and Blueskin Bays where the well-developed Holocene sand wedge (w1–3) extends to wedge w4 of presumed 12,000-year age, and wedge w5 of probable 15,000-year age.

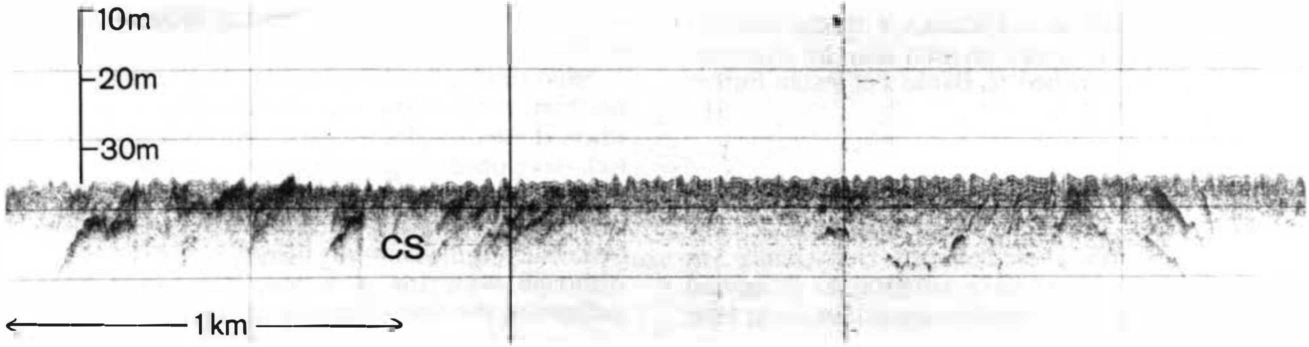
3.5 kHz seismic profiles show that the seaward edge of the spit overlaps middle shelf relict deposits along a gently tapered edge (Figs 6, 9). The main body of the spit is massive and acoustically absorbent, a seismic characteristic consistent with it being composed of well-sorted sand. A single reflecting horizon occurs subparallel to and about 7 m beneath the spit surface, especially towards its southern end. The sediment above this reflector thickens west across Blueskin Bay and then tapers out again against the sands of the western shoreface of the Bay. The muddy sand above the reflector in central Blueskin Bay is almost certainly a modern deposit. It is surprisingly thin, which suggests the hydraulic conditions in the central bay barely permit deposition of suspended load.

The genesis of the Peninsula Spit is controversial. Marshall (unpublished 1931 report to the Otago Harbour Board) and Schofield (1976) concluded it was a modern feature formed by deposition from north-flowing inshore currents. Andrews (1973, 1976) preferred to interpret the feature as a spit formed during a sea level still-stand at c.8,000–9,000 years B.P. and subsequently drowned by the final phase of the post-glacial transgression. Andrew's argument turns largely on the fact that textural parameters show a complex distribution pattern along the crest of the bar, which he therefore claims is not in equilibrium with modern hydrology.

The throughput of sediment off the Otago Peninsula is large, between 450,000 m^3 y^{-1} (Kirk, unpublished 1980 report to the Otago Harbour Board) and 1,000,000 m^3 y^{-1} (Gibb 1979). The main sources, ultimately the rivers to the south, provide sediment with textural attributes similar to those of the Peninsula Spit, including a range of grain sizes that encompasses the complex distribution patterns recorded by Andrews (1973, 1976). Furthermore, these patterns could be influenced by local input from the Otago Peninsula. Thus, with an ample supply of modern sediments of the right grain size we see no reason to invoke the spit as a relict feature, particularly since it lies directly along the main path of the modern shoreline-inner

FIG. 7(*opposite*). Representative 3.5 kHz seismic profiles of the inner to middle continental shelf offshore from Karitane. Note the presence of buried channels (c) filled with Late Pleistocene sediment (lp), tilted and folded Cenozoic sediment (cs) locally outcropping, and volcanic pinnacles (vp). The youngest sediment wedge (pg) has not been cored but is certainly post-glacial, either relict-palimpsest or modern.


20m
30m
pg
lp
C
C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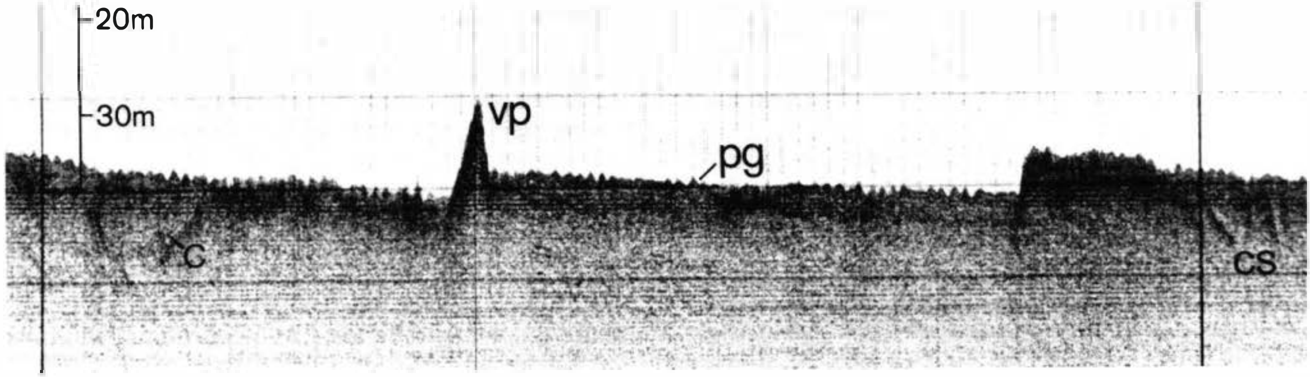
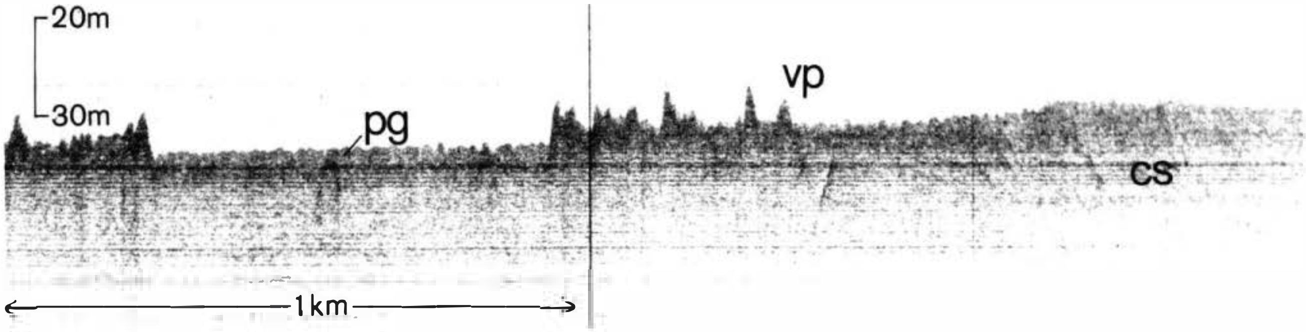

20m
30m
vp
pg
C
cs


20m
30m
pg
vp
cs
1km

shelf transport route. The distribution patterns of Andrews (1973) could equally stem from fluctuations in the modern sediment supply or hydraulic regime, or from other factors discussed by Schofield (1976). However, the top surface of at least the south end of the Peninsula Spit is levelled at about −20 m, probably an effect of fair weather wave base in the area; sediment above this level is presumably transported either landward into the harbour mouth system (Kirk, unpublished 1980 report to the Otago Harbour Board) or northwards.

It is certainly possible that the internal reflector within the Peninsula Spit could well mark the position of an earlier, and possibly 8,000–9,000-year-old spit, as suggested by Andrews (1973). Nonetheless, the present surficial sedimentology and bathymetry of the bar are undoubtedly in equilibrium with modern currents and sediment supply, as seen also, for example, in a similar spit attached to Banks Peninsula further north (Herzer 1981).

Bedforms

The prominent bulge in the modern sand wedge in the north Taieri Bight gives way to a field of large sand waves (Fig. 10). These bedforms are typically 5 m high, single crested, and have wavelengths of around 400 m. Wave crests are laterally continuous for at least several hundred metres, and are oriented in a north-west–south-east direction, with their steeper, lee faces pointing south-west. The inferred direction of transport is opposite to the regional trend and may reflect a localised current generated by deflection of the prevailing flow against the Otago Peninsula. But, until diagnostic current meter data are available, the cause and dynamics of this proposed counter-current must remain speculative.

The sonographs also revealed small, symmetric gravel dunes of 2–4 m wavelength within the wave troughs; the direction of gravel dune migration being perpendicular to that of the sand wave (*cf.* Bouma *et al.* 1980). The seismic stratigraphy (Fig. 10), bottom samples, and piston cores indicate that the gravel dunes are part of the underlying relict gravel sheet which is being reworked by modern currents flowing along the sand wave troughs. The apparent symmetry of the gravel dunes and their alignment with a prominent direction of swell approach (Pickrill and Mitchell 1979) suggest these bedforms may be wave-induced, although some linear flow component must also be present to remove the sand cover.

The north-eastern end of the wave field displays evidence of sediment starvation, with isolated sand waves scattered across the gravel substrate; individual waves here are generally of barchan shape rather than straight-crested as further south. This edge to the wave field coincides with the major shoreward re-entrant of the modern sand wedge.

Development of sand waves requires a rapidly flowing current. The bedform/depth/grain size plots of Rubin and McCulloch (1980) point to current speeds of 90–160 cm s^{-1} as being necessary for wave development in fine sand at 40 m depth. The confinement of the sand wave field to the environs of the Otago Peninsula implies that the relatively strong tidal flow and Southland Current in this area plays a part in sand wave formation. However, the limited amount of current data available indicates the combined speed of these currents is of the order of 40–50 cm s^{-1}, which is well below the necessary threshold of 90 cm s^{-1}. To reach the required speed, normal currents would have to be reinforced by motions associated with major storms, e.g., storm-force winds of 125 km h^{-1} would generate significant wind-drift currents with speeds of 35–40 cm s^{-1} at 40 m depth. Thus, we conclude the sand waves are a response to storm-reinforced currents in much the same manner as those documented by Field *et al.* (1981).

Sand ripples were detected in photographs from the northern limit of the modern terrigenous sand facies where it intermingles with relict gravel (Fig. 11d). Here, well-developed cuspate forms with apparent symmetric outlines have formed in a patchy sand veneer overlying gravel. Ripple crests trend north-west–south-east, which is the common direction of swell approach. Although occurring in a zone dominated by relict sediments, the rippled sand is modern rather than palimpsest judging by its petrographic characteristics of fine grain size, fresh, unstained grains, and quartz-feldspar-mica composition (Station Q256).

Modern terrigenous mud

At least 50% of the river sediment input to the South Otago shelf is mud, judging by the grain size of Clutha River sediment (Jowett and Hicks 1981). Yet the South Otago shelf is overwhelmingly dominated by sand and gravel. What is the fate of the mud?

The limited satellite imagery available (*Landsat* II and *Nimbus* VII) shows that plumes of muddy river water travel north-eastwards along the eastern South Island shelf (Fig. 12). In southerly storm conditions the plumes travel close inshore over the inner shelf under the influence of the Coriolis-deflected wind drift (cf. Carter and Herzer 1979; Carter *et al.* 1982). In calms and light northerly winds the plumes are more diffuse and may spread to the middle shelf, but they generally retain their north-eastward drift. Thus at least part of the suspended load, i.e., that visible on satellite imagery, bypasses the obvious mud depocentre off Otago, namely, the Bounty Trough. However, cores from the trough rim indicate it is the recipient of modern terrigenous mud (Griggs *et al.* 1983) although this contribution is small compared to the calcareous pelagic contribution which dominates trough sedimentation (*see*, e.g., McDougall 1982). The mechanism by which mud reaches the Bounty Trough is unclear but it may be similar to the "mud hopping" mechanism propounded by Pilkey *et al.* (1978). Certainly, mud that has temporarily accumulated on the

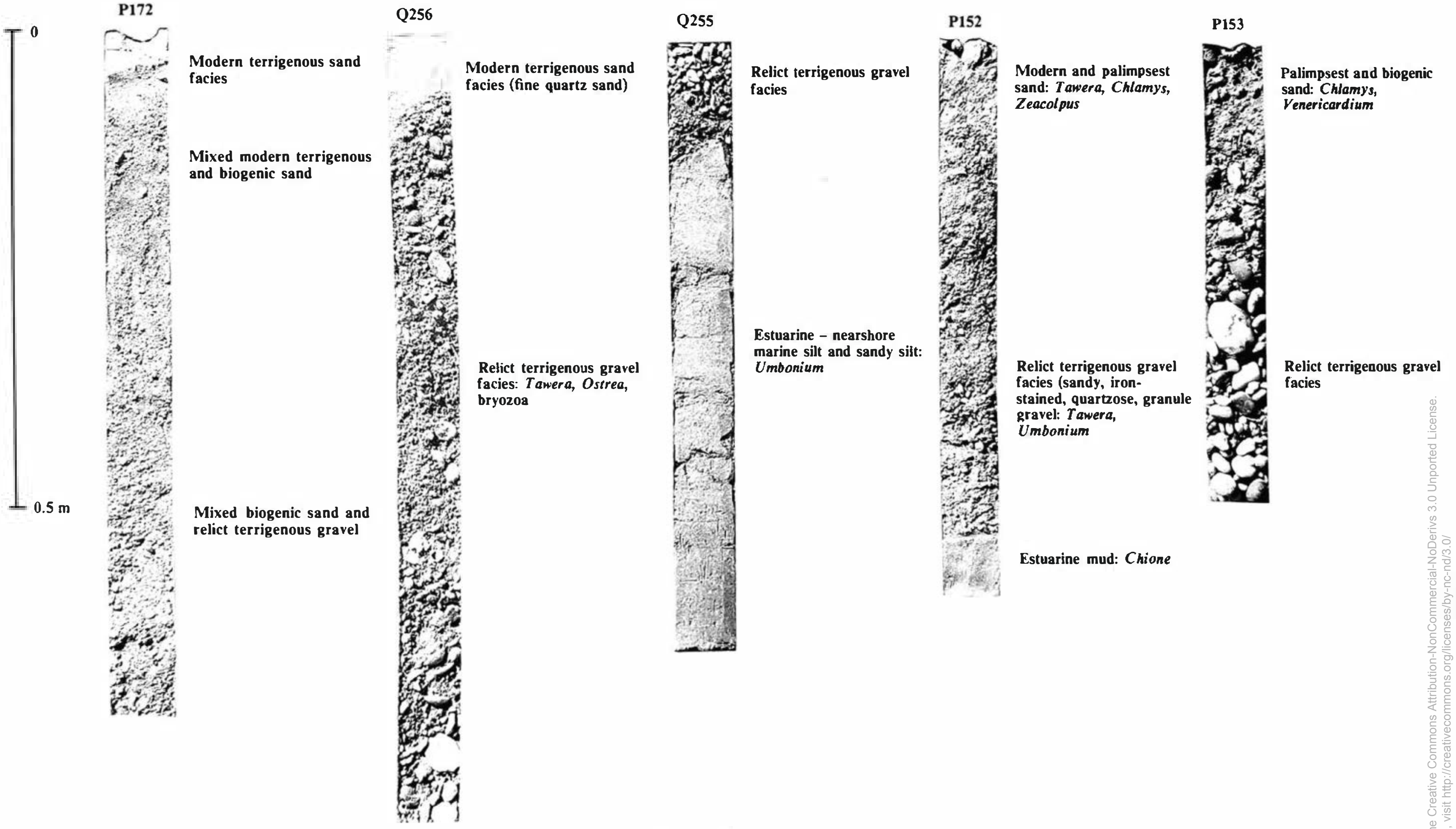


FIG. 8. A suite of piston cores displaying the lithologies and stratigraphic relationships of the main sediment facies on the South Otago continental shelf. P172 is from the seaward edge of the Clutha sediment wedge, Q256 from the northern limit of the modern terrigenous sand facies, Q255 from the edge of the Saunders Ridges, and P152 and P153 from the terrigenous/biogenic palimpsest cover of the middle to outer shelf off the Otago Peninsula.

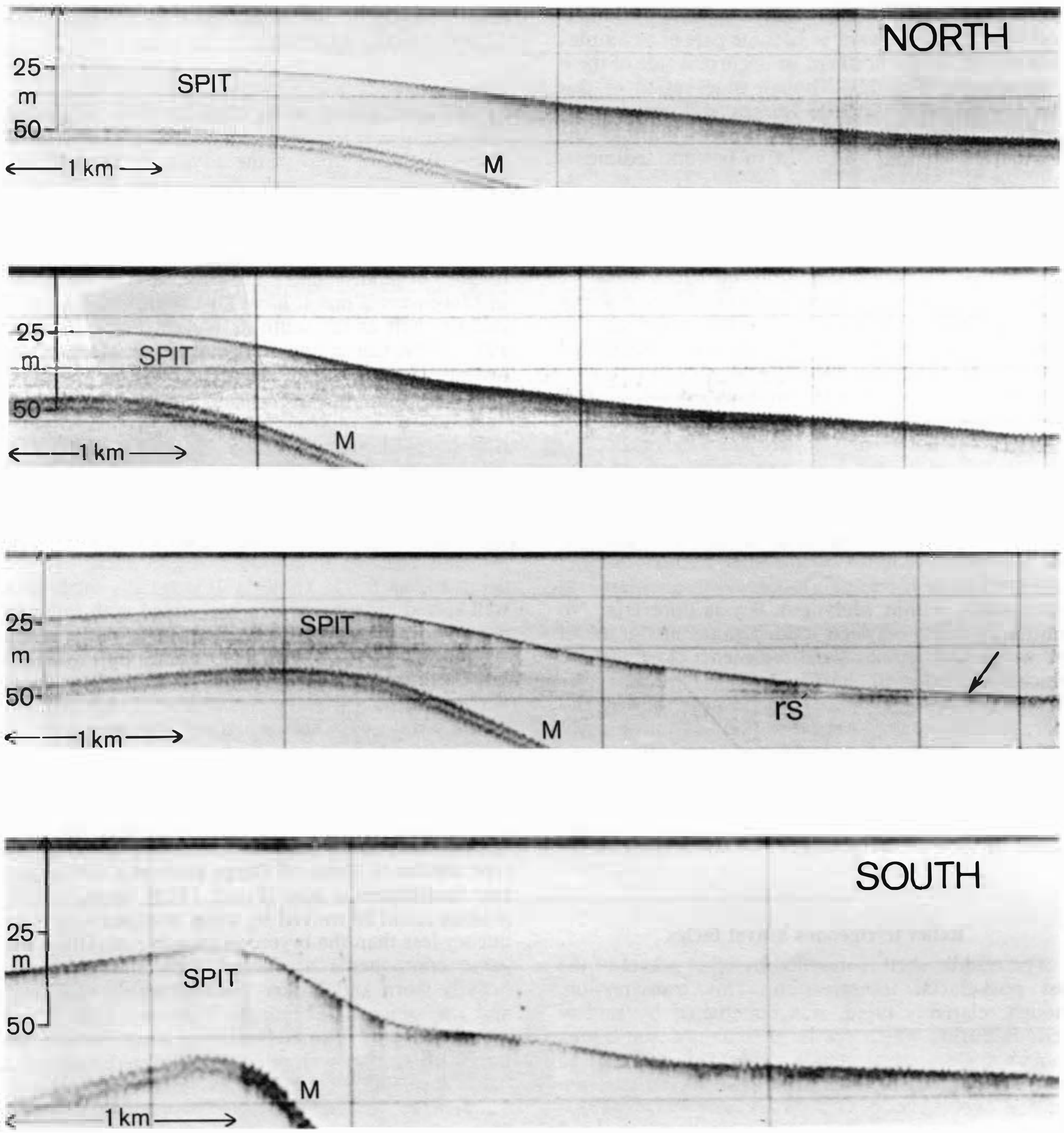


FIG. 9. East-west 3.5 kHz seismic profiles across the Otago Peninsula submarine spit. The lack of acoustic penetration implies a massive sand substrate. The seaward edge of the spit (arrowed) laps on to relict sediments of the middle shelf (rs). Note the gentle seaward (constructional) profile towards the northern tip of the bar, in contrast to the steeper (erosive) profile further south. Echo multiple = m.

middle shelf could be transported seaward by bottom currents generated during southerly storms as a compensatory response to the onshore build-up of water by the Ekman component of the wind drift.

The sediment-laden water moving along the inner shelf impinges on Nugget Point and the Otago Peninsula, resulting in both cases in divergences of the flow with one branch being deflected seaward over the middle shelf and the other branch spiralling counterclockwise and shoreward to become part of a complex eddy system on the northern or upcurrent side of these promontories (Fig. 12). Though observation of this flow is limited to satellite images and aerial overflights (J. Jillett, Otago University, pers. comm.), the distribution of mud and mica in bottom sediments confirms the divergent flow patterns (Loutit 1975; Williams 1979). On a given occasion the relative importance of the two diverging branches probably depends on meteorological conditions. During southerly storms divergence is minimised by the onshore Ekman component and most suspended load is swept inshore. Under northerly conditions, when an offshore Ekman component prevails, more suspended load will be directed seaward.

In the vicinity of Nugget Point and Molyneux Bay the distribution of suspended and deposited mud has a pattern similar to that off the Otago Peninsula, but the controlling factors are different. Plumes of sediment from rivers south of Nugget Point move seaward of the Point and back towards Molyneux Bay. The distribution of muddy sand at the toe of the Clutha sediment wedge confirms this trend (Andrews 1979). Whether the southern-derived mud enters and accumulates within Molyneux Bay is uncertain. No continuity exists between muddy sands at the toe of the wedge and similar sized sediments close inshore which are related to the Clutha River mouth. This means the southern muds either bypass the bay offshore, or, if they are swept into the bay, fail to accumulate on account of the meagre protection from southerly storms offered by Nugget Point. Of course, mud may eventually settle out in the deep recesses of the bay, but the mud there is probably Clutha-dominated in view of the proximity of this large river.

Relict terrigenous gravel facies

The middle shelf is mantled by relict gravel of the last post-glacial transgression. This transgression, though relatively rapid, was punctuated by several periods during which sea level remained static long enough for stable shoreline wedges of sediment to develop. We accept here without further discussion the sea-level curves of Gibb (1979) and Herzer (1981) as representing the present best estimate for sea-level behaviour in New Zealand over the last 20,000 years. According to these authors sea level reached the present datum at c.6,500 years B.P. after occupying several successively shallower shorelines, now drowned, during pauses in the transgression at around 15,000, 12,000, 10,000, 9,000, and 7,500 years B.P.

Distribution

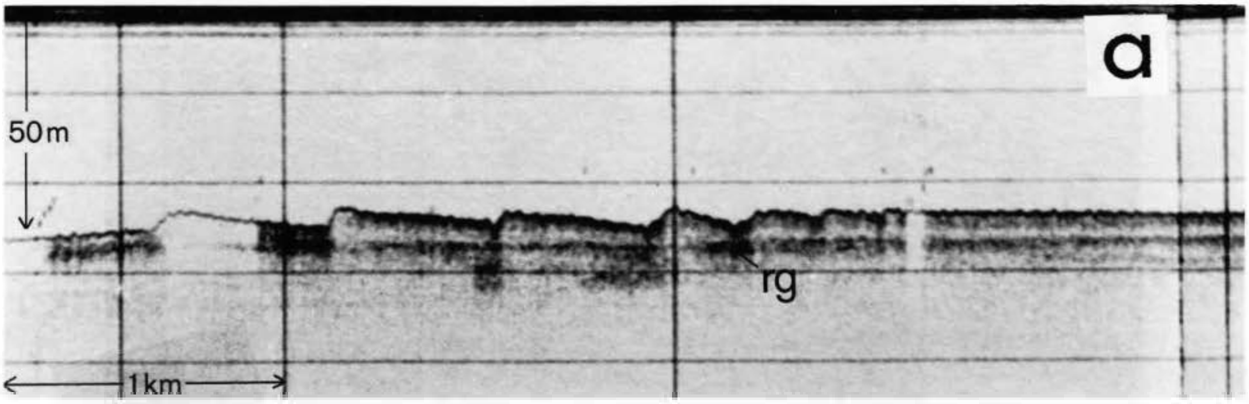
The relict gravel facies takes the form of a north-east–south-west trending belt which is widest off the Taieri Bight, in front of the advancing modern sand wedge (Fig. 4). The main body of the facies lies in depths of 50–65 m with a total depth range of 30–80 m or deeper where the shelf is incised by submarine canyons. Patches of relict gravel, isolated by tongues of modern and palimpsest sand or by patches of biogenic sediment, have also been located on the middle shelf as far south as Nugget Point (Andrews 1973, 1979; Carter and Ridgway 1974). Modern sand has also leaked on to the main body of the gravel facies in the Taieri Bight, where tongues of sand move north-eastward along the troughs between gravel ridges.

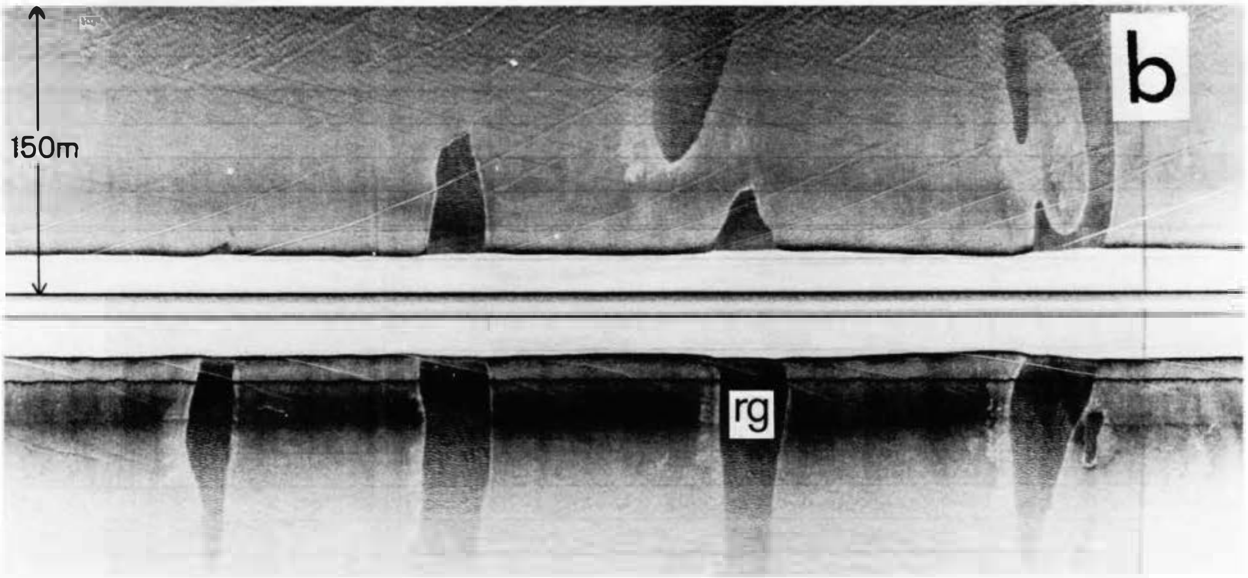
Petrography and Provenance

The gravel comprises rounded to well-rounded clasts of yellow to cream vein quartz that is typically iron-stained. Minor amounts of greywacke are also present (Figs 8, 11; Table 1). It is usually moderately well sorted except where it has mixed with sediment from other facies (Fig. 5). The mean grain size is around 6 mm(−2.5ϕ) although pebbles up to 100 mm longest diameter are occasionally found. These larger pebbles commonly carry epifaunal encrustations, particularly bryozoa, whereas pebbles < 10 mm diameter are usually clean, implying that they are still subject to transport (Andrews 1973; Williams 1979). However, it should be emphasised that the presence of bryozoan encrustations does not necessarily mean the large pebbles are immobile. Encrusting bryozoa of a type similar to those off Otago grow at a rate of several centimetres a year (Friedl 1925), so these large pebbles could be moved by water motions with a frequency less than the bryozoan growth rate. Other biogenic components associated with the gravel are heavily worn and broken shells, notably of *Tawera* and *Zeacolpus*, and bryozoan fragments (Figs 8, 11).

The gravel is ultimately derived from Haast Schist terrain. It has been supplied more immediately either (i) via the Clutha River (Andrews 1973), or (ii) via the Taieri River, or (iii) from the erosion of outcrops of Taratu Formation on the seafloor (Marshall, unpublished 1931 report to the Otago Harbour Board). The last possibility has been discounted by most workers since suitable submarine outcrops have not been found. On the basis of sparse samples, Andrews (1973)

FIG. 10(*opposite*). (a) 3.5 kHz seismic profile across the sand wave field in the north Taieri Bight. The prominent sub-bottom reflector (rg) is a thin sheet of reworked relict gravel. (b, c) Side-scan sonographs of sand waves on the middle shelf in the Taieri Bight. Tracks run along the shelf, perpendicular to wave crests. The discontinuous ribbons of duned sediment in the sand wave troughs are reworked exposures of underlying relict gravel (rg).


a
50m
rg
1km


b
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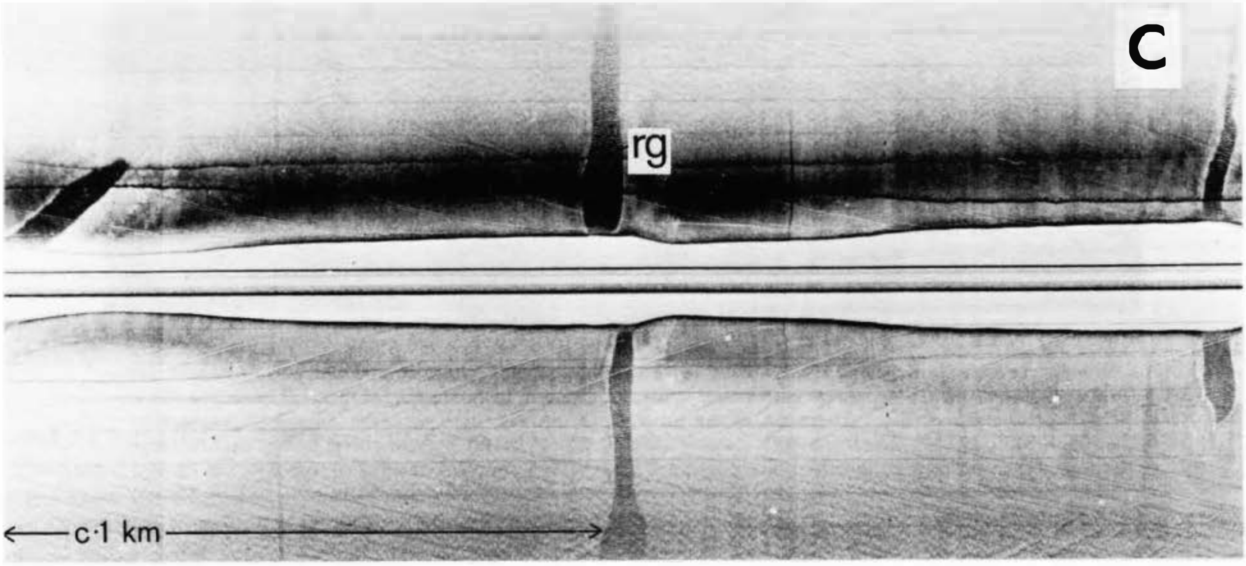
rg


c
rg
c·1 km

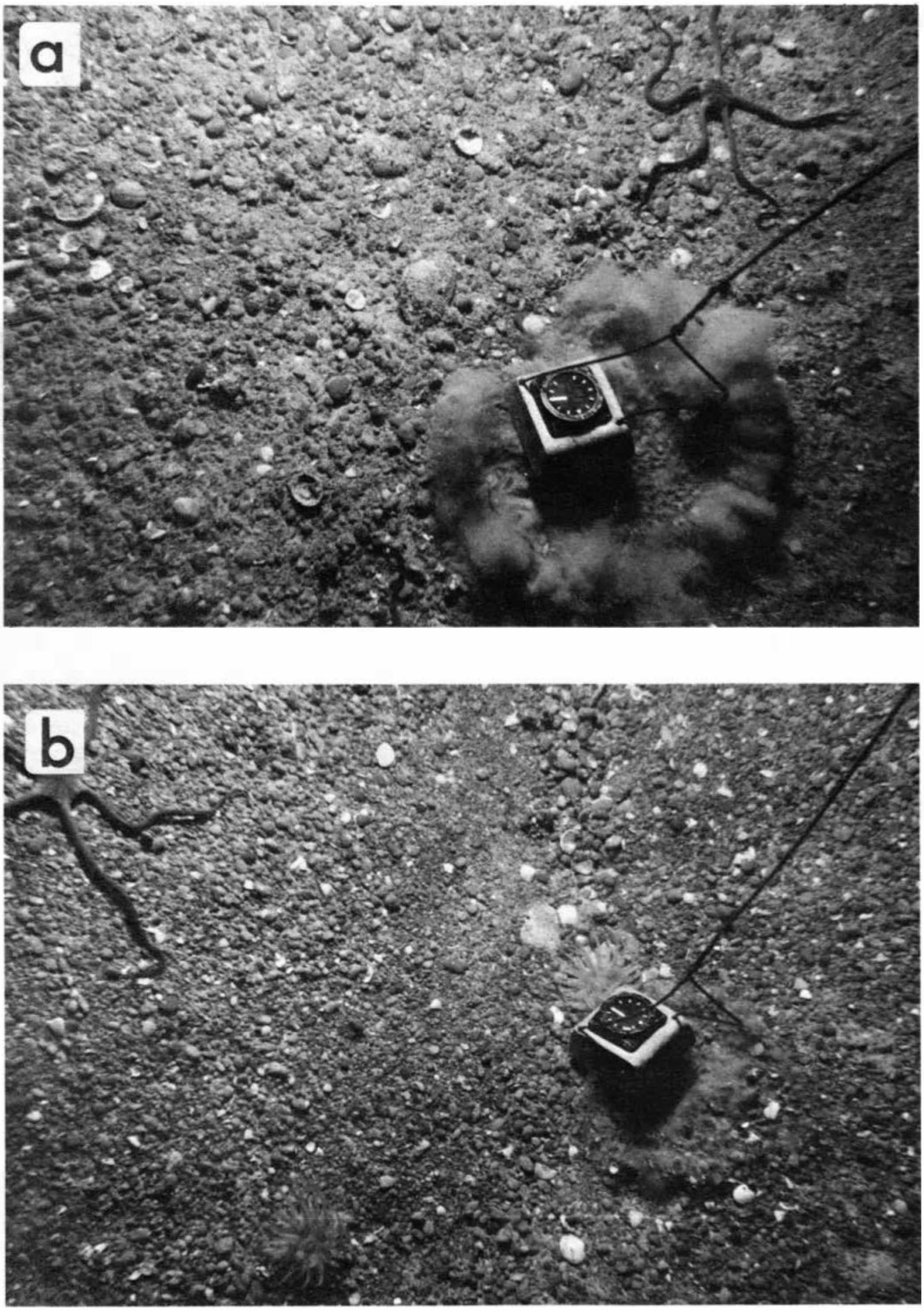
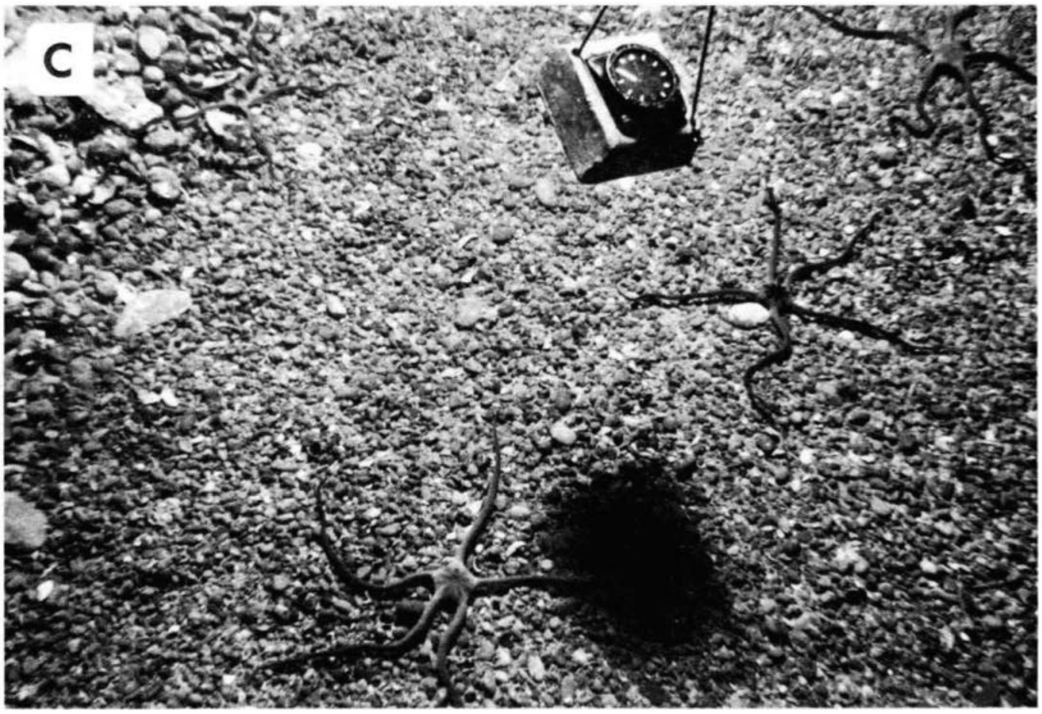


FIG. 11(*above and opposite*). Bottom photographs of the relict terrigenous gravel facies at the Saunders Ridges (compass is 8 cm on a side). Conspicuous epifauna of *Pectinura maculata* and *Ophiactis*. (a) Inner flank of inner ridge, gravel with a thin veneer of modern, inshore sand. Station Q254, depth 46 m. (b) Typical clean, well-sorted gravels of the inner ridge, showing size variation related to presence of dunes advancing from the south-east. Station Q254, depth 46 m. (c) Typical gravel on the middle ridge showing dune sorting in top left corner. Station Q255, depth 51 m. (d) Gravel with thin cover of rippled sand derived from the south-east photographed in depression between middle and outer ridges. Station Q256, depth 56 m.



favoured a Clutha River origin for the gravel. At former low stands of sea level, the main transport route along the shelf may have been deflected by a headland just south of the present Taieri River mouth, as suggested by submarine outcrops of Caversham Sandstone at Station P176. Thus, it is possible that there were two separate gravel belts, that within the Taieri Bight coming from the Taieri River. However, the Clutha River has been a much greater supplier of sediment than the Taieri because of the size and type of

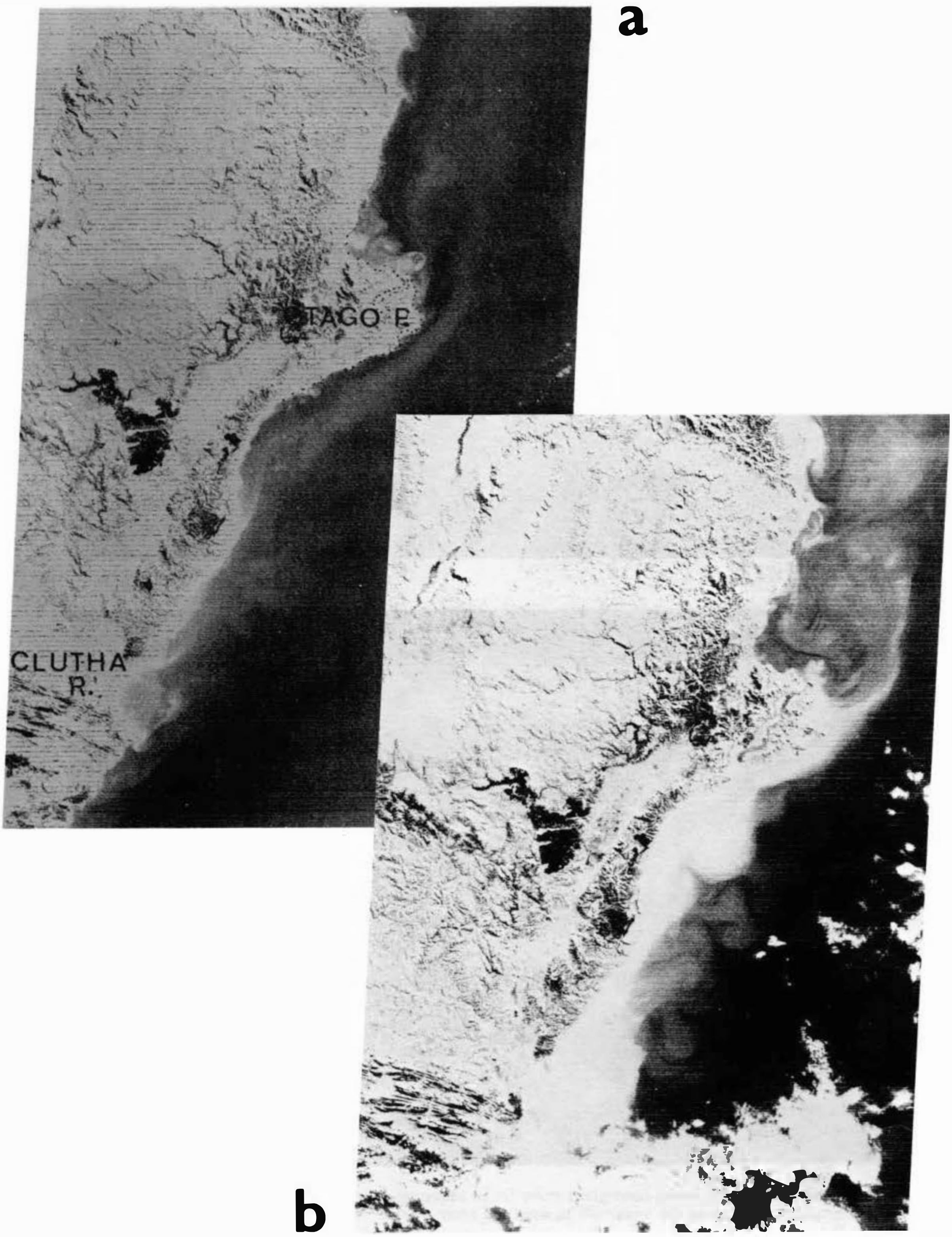


FIG. 12. *Landsat* II imagery showing the dispersal paths of the predominantly Clutha River-derived suspended sediment along the Otago continental shelf. Note the bifurcation of the sediment plume off the Otago Peninsula and the complex eddy within Blueskin Bay. a = ref.49, and b = ref.302 of the Physics and Engineering Laboratory *Landsat* II image collection, DSIR, Wellington.

the Clutha catchment. Unless a discontinuity can be demonstrated within the gravel belt, a Clutha-dominated source remains most likely. The *in situ* sand component associated with the gravel facies in cores is also of Haast Schist provenance.

Bedforms

Features of the relict gravel facies are the Saunders Ridges in the northern sector of the Taieri Bight, just south of Cape Saunders (Figs 1, 3). The three large, parallel ridges lie in depths of 44–60 m and are aligned almost directly north-east–south-west. Spacing between ridge crests is approximately 1 km, crest amplitudes reach 10 m and the individual ridges have a longitudinal extent of some 25 km (Fig. 3). The outer ridge contrasts with the others in having a flat top, suggesting that the crest has been truncated by erosion. The middle ridge also has a subdued expression, with a morphology on its inner side consistent with the reworking of sediment into the adjacent trough (Fig. 13).

Dunes with wavelengths of 1–3 m, amplitudes of < 1 m, and symmetrical profiles are virtually ubiquitous throughout the area of gravel distribution (Fig. 14). Dune crests trend approximately east-north-east inshore of the Saunders Ridges, but have an east-south-east trend along the ridge crests themselves. The former direction approximates the general approach of the omnipresent southerly swell in this region (Pickrill and Mitchell 1979), with the dunes on ridge crests possibly showing some response to the prevailing north-easterly currents or channelisation of currents between the ridge crests.

Stratigraphy

The relict gravel facies reaches a maximum thickness of 15 m below the crests of the Saunders Ridges and is essentially structureless apart from a few thin reflectors interpreted as sand layers (Figs 8, 13). Elsewhere, the gravel occurs as a 0.3–1.0 m thick veneer above a conspicuous reflecting horizon, which may locally crop out in the troughs of the ridge system (Fig. 13). Piston cores P152, Q253, and Q255 all penetrated to this reflector — a massive, grey, non-calcareous, bioturbated silt and mud which in Q255 grades down to shoreface sandy sediment with *Umbonium* (Fig. 8). In core P152 the mud is estuarine, containing a fresh, double-valved *Chione* with a radiocarbon age of 12,150 ± 300 y B.P. (^{14}C NZ4619).

In situ gravel is probably confined to the three Saunders Ridges, which we interpret to have been built upon shoreface and estuarine sediment at a 12,000-year-old, Late Pleistocene shoreline, here preserved at a depth of c.55 m. The thin gravel sheet inshore and north of the ridges is probably reworked. Grain size analyses (Williams 1979) display a progressive fining of the gravel sheet from the ridges to the Otago Peninsula, strongly implying the ridges are the source of the gravel veneer. However, close to the Peninsula the trend is reversed, possibly as a consequence of the strong flow removing the finest gravel fraction. Textural trends across the shelf are not so obvious, but in general there is a fining of the gravel fraction from ridge crests to troughs in both landward and seaward directions.

Though gravel has been recovered from bottom samples over a wide area outside the ridge system, it is so thin as to be undetectable on seismic profiles. Sonographs show the presence of "windows" in the gravel, which, though generally less than 1 m thick, is nonetheless present in sufficient quantities to largely cover the seabed (Figs 8, 14; cf. Newton *et al.* 1973). Inshore of the inner ridge the thin gravel sheet is underlain by relatively complex stratigraphy with up to three reflectors visible. This zone becomes narrower to the south and its morphology, particularly the landward termination of sediment wedges against buried erosional notches, suggests accumulation against an old embayed shoreline at around 55 m depth.

Origin of the Saunders Ridges

The evidence indicates that the ridges are not genetically related to modern sea level. First, the sediment is considered to be relict because: (i) the depth of occurrence of the gravel is inconsistent with the modern sediment supply and hydraulic regime; (ii) many clasts are iron-stained and, whether caused by subaerial (James and Stanley 1968) or subaqueous (Milliman 1972) weathering, an appreciable period of time is required to produce this effect; (iii) clasts greater than granule size are generally epizoan encrusted, suggesting they are either static or infrequently moved on the seafloor; (iv) the gravel is associated with relict faunas, including estuarine forms in an underlying mud; and (v) surface textures of quartz sand associated with the gravel frequently show aeolian features, including upturned cleavage plates (Williams 1979; Margolis and Krinsley 1974). Second, the erosion of the middle and outer ridges, and the redistribution of the granule fraction as a palimpsest sheet over a wide area, suggests ridge formation took place under a hydraulic regime different to that at present.

Long, parallel, constructional ridges can form in several shoreline and offshore environments. However, the Saunders Ridges are perhaps best interpreted as shoreline barrier deposits (e.g., Hails and Gostin 1978), an interpretation that is consistent with their coarse grain size and association with underlying shoreface and estuarine deposits. The formation of these parallel ridges might be due either to construction by successive phases of storm activity or, alternatively, to minor regressive phases during the 12,000-year shoreline still-stand.

Preservation of the Saunders Ridges in their present mid-shelf position, with only minor erosion by post-12,000-year processes, requires that ridge for-

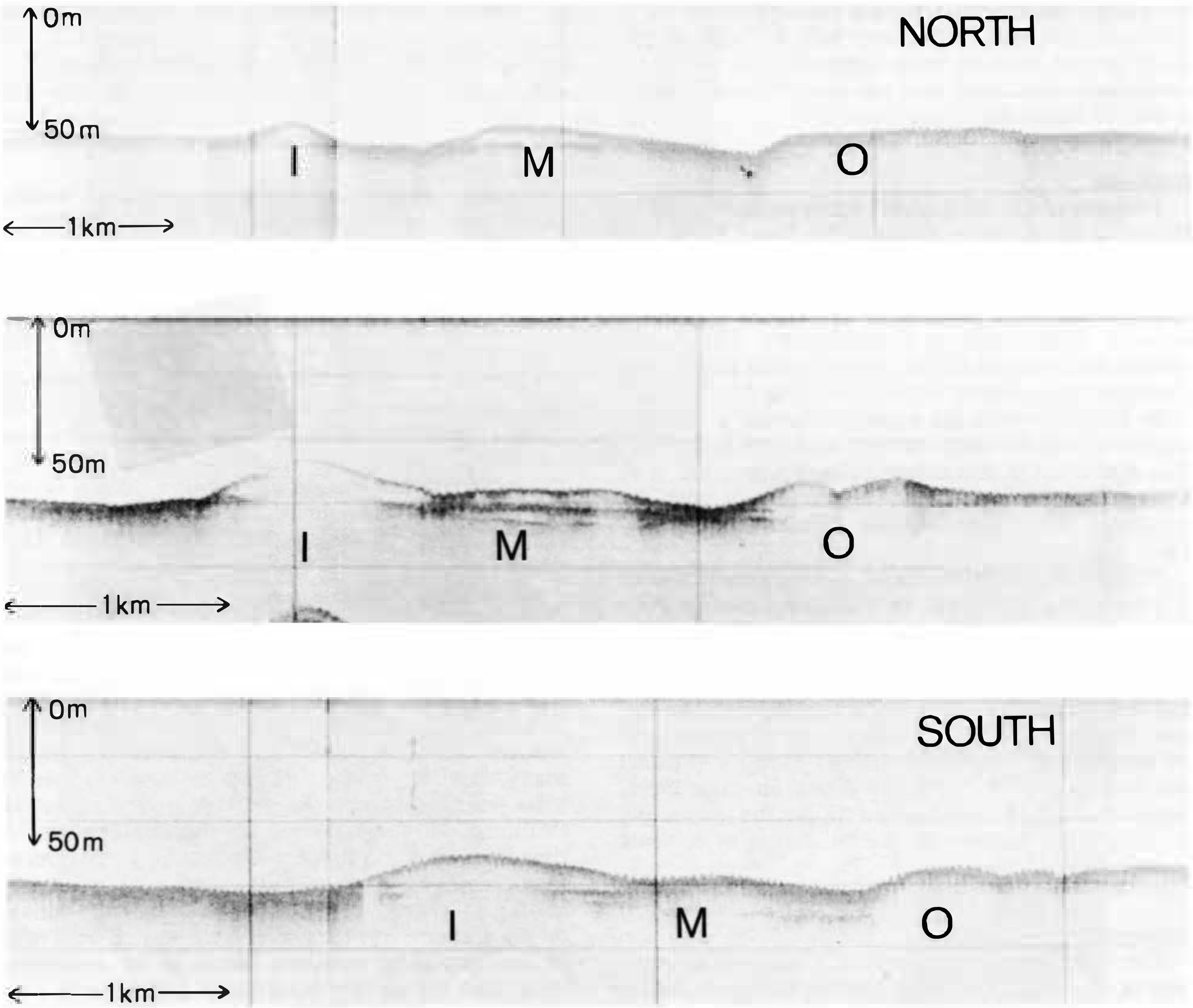


FIG. 13. 3.5 kHz seismic profiles across the Saunders Ridges from north to south, showing inner (I), middle (M), and outer (O) ridges. The prominent sub-bottom reflector is mud and sand of relict estuarine deposits.

mation be followed by a relatively rapid movement of the shoreline across the shelf to its next quasi-stable position at a depth of about 30 m (c.10,000 years B.P.). Therefore, the model of a shoreline barrier continuously migrating inshore as the sea level rises (Swift 1968) is not applicable to the Saunders example. It seems rather that an extremely rapid rise of sea level between 12,000 and 9,000 years B.P. (cf. Cullen 1967) resulted in the *in situ* drowning of the ridges to a depth below normal nearshore wave base, with the shoreline effectively vaulting from one position to the next in the fashion envisaged by Sanders and Kumar (1975) for sand barriers off Long Island, New York. The thin and extensive sheet of reworked gravel inshore of the ridges may nonetheless have been deposited as a classic "transgressive sheet" during the movement of the shoreline through to 30 m depth and shallower, but it is clear that at least minor reworking of the main ridge gravel deposits continues today.

Relict/palimpsest sand facies

Distribution

Terrigenous sands deposited at a lower stand(s) of sea level form an ill-defined middle to outer shelf belt marginal to the modern terrigenous sand and relict terrigenous gravel facies (Fig. 4). South of the Tokomairiro River mouth the facies has been largely inun-

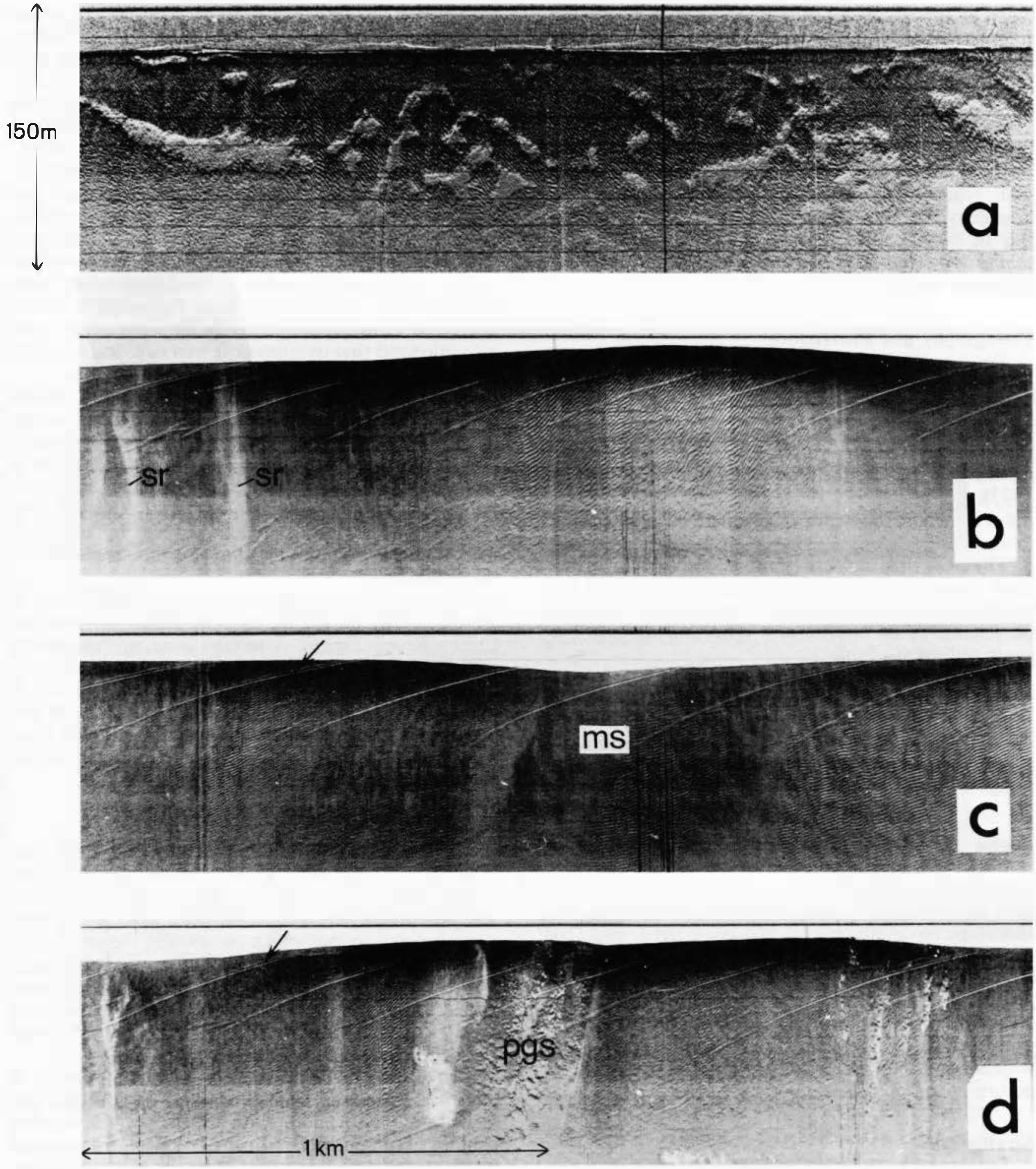


FIG. 14. Side-scan sonographs of the relict terrigenous gravel facies including the Saunders Ridges. Ignore artefacts (arrowed) due to paper creases; right channel only reproduced. (a) Windows through a thin blanket of gravel, reworked inshore and north-west of the Saunders Ridges. (b) Transect across the inner ridge. Pattern of gravel dunes, fading out on inshore flank of ridge, and locally covered with narrow, mobile sand-ribbons (sr) on the offshore flank. (c) Depression between the dune-covered inner and middle ridges, containing a patchy veneer of mobile sand (ms). (d) Transect across outer ridge. Duned gravel with occasional sand ribbons. Bipartite morphology of the ridge in this transect is interpreted as due to erosion, which has also exposed probable consolidated post-glacial silts (pgs) underlying the gravel in the centre and on the inner edge of the ridge.

dated by the advancing modern sand wedge. From the river northwards, however, the facies is well exposed on the middle shelf between 55 and 75 m depth off the Tokomairiro River, between 75 and 90 m depth off the Otago Peninsula, and between 30 and 55 m depth off Blueskin Bay. Both the landward and seaward limits of the facies are diffuse, with the sand freely intermingling with modern sand inshore and with relict gravel and biogenic sand offshore. The boundary with the modern sand facies off Molyneux Bay is, however, better defined, perhaps in response to the bathymetric barrier presented by the Clutha sediment wedge.

Petrography and Provenance

Compared to modern sand, relict/palimpsest sand is distinctly coarser (fine to medium grade) and more poorly sorted, mainly on account of mixing with relict terrigenous and biogenic gravel (Fig. 5, Table 1). Off Blueskin Bay, relict/palimpsest sand has sorting values further degraded by the accumulation of silt (Andrews 1973), doubtless because it lies beneath one of the main transport routes for the modern shelf suspended load.

The relict/palimpsest sand is also distinguished from its modern counterpart by being iron-stained and possessing a higher mean carbonate value, the latter on account of its mixing with relict and modern biogenic sediment (Table 1).

The dominant light terrigenous components are quartz, K feldspar and plagioclase, and the heavy mineral assemblage is mainly hornblende, hypersthene, garnet, and epidote-clinozoisite, suggesting a mixed provenance from Haast Schist and Foveaux Strait-Western Province sources (Table 1).

Fauna

Relict faunal elements of the middle shelf include *Struthiolaria, Umbonium (Zethalia)*, and *Antisolarium*, all of which are normally associated with shallow shoreface environments on the inner shelf, and thus occur here well below their normal depth range (cf. Probert 1977). Several *Umbonium* from 95 m depth yielded a radiocarbon age of 10,050 ± 250 y (^{14}C NZ4618), which should be treated as a minimum because of minor modern bryozoan encrustation, but which serves to establish beyond doubt the relict nature of the sample.

Stratigraphy

Sediments of the relict/palimpsest facies may represent (i) wedges deposited at quasi-stable shorelines during pauses in the post-glacial transgression and/or (ii) parts of the transgressive sand sheet generated during phases of rapid shoreline movement of the same overall transgression. In either case, the sediments have been subsequently modified by modern currents, and as a consequence stratigraphic relations are varied. The mobile palimpsest component of the facies may, for example, cover or mix with sediments of any other stratigraphic unit on the continental shelf (Fig. 8). The picture is further complicated by difficulties in identifying the often thinly bedded sands on seismic profiles. Nevertheless, we can draw several conclusions from the seismic and core data at hand.

Off Blueskin Bay the main body of the facies is coincident with, and as far as we can ascertain, part of a prominent sediment wedge built against a terrace at 55 m depth (Fig. 6), i.e., against the 12,000-year "Saunders Ridge" shoreline. The landward edge of the wedge is covered by modern sand emanating from Blueskin Bay, whereas to seaward the wedge thins out at around 72 m depth and the facies intermingles with biogenic sand that overlies or is part of a deeper, older sediment wedge formed at 75 m depth (Fig. 6).

In the Taieri Bight the sand appears quite thin and does not form a readily identifiable sediment wedge. It thinly mantles the seaward margin of the relict gravel facies, which itself may have acted as a secondary source of the sand through Holocene "unmixing" (*see* Swift *et al.* 1971). The relict/palimpsest sands are also covered by, or mixed with, modern sand moving along the middle shelf from the south-west.

Off Molyneux Bay the facies on the middle shelf is almost totally buried by modern sediment from the Clutha River (Fig. 6). A terrace level, corresponding to the − 55 m terrace further north, is just discernible beneath the Clutha sediment wedge. The terrace is devoid of its own wedge, which, together with the occurrence of numerous subcrops of presumed Cenozoic rock, implies that the relict sand cover is very thin in this area (Fig. 6).

The − 110 to − 120 m Shoreline

Terrigenous sands, interpreted as relict, have also been detected in deeper water at the shelf edge off the Otago Peninsula and Nugget Point (Andrews 1973). The sediments here are in intimate association with a conspicuous terrace which occurs near the shelf break at depths of 110–120 m, especially around the heads of the Otago canyons (Fig. 15). The terrace is interpreted as a feature cut at the time of lowest sea level at the peak of the last glaciation, c.18,000–20,000 years B.P.

The sediments have the petrographic attributes of the middle to outer shelf sands and, in addition, are sometimes associated with flattened, bio-eroded pebbles of cemented Cenozoic siltstone and sandstone which commonly carry dark, iron oxide-rich crust, suggestive of their having been exposed for long periods on the seafloor.

These shelf edge sands are commonly associated with abundant dead *Zeacolpus* (*Stiracolpus*), minute bivalves, *Antisolarium*, and a relict shallow-water fauna that includes fresh specimens of *Paphirus largillierti, Tawera spissa* phentotype *subsulcata*, and

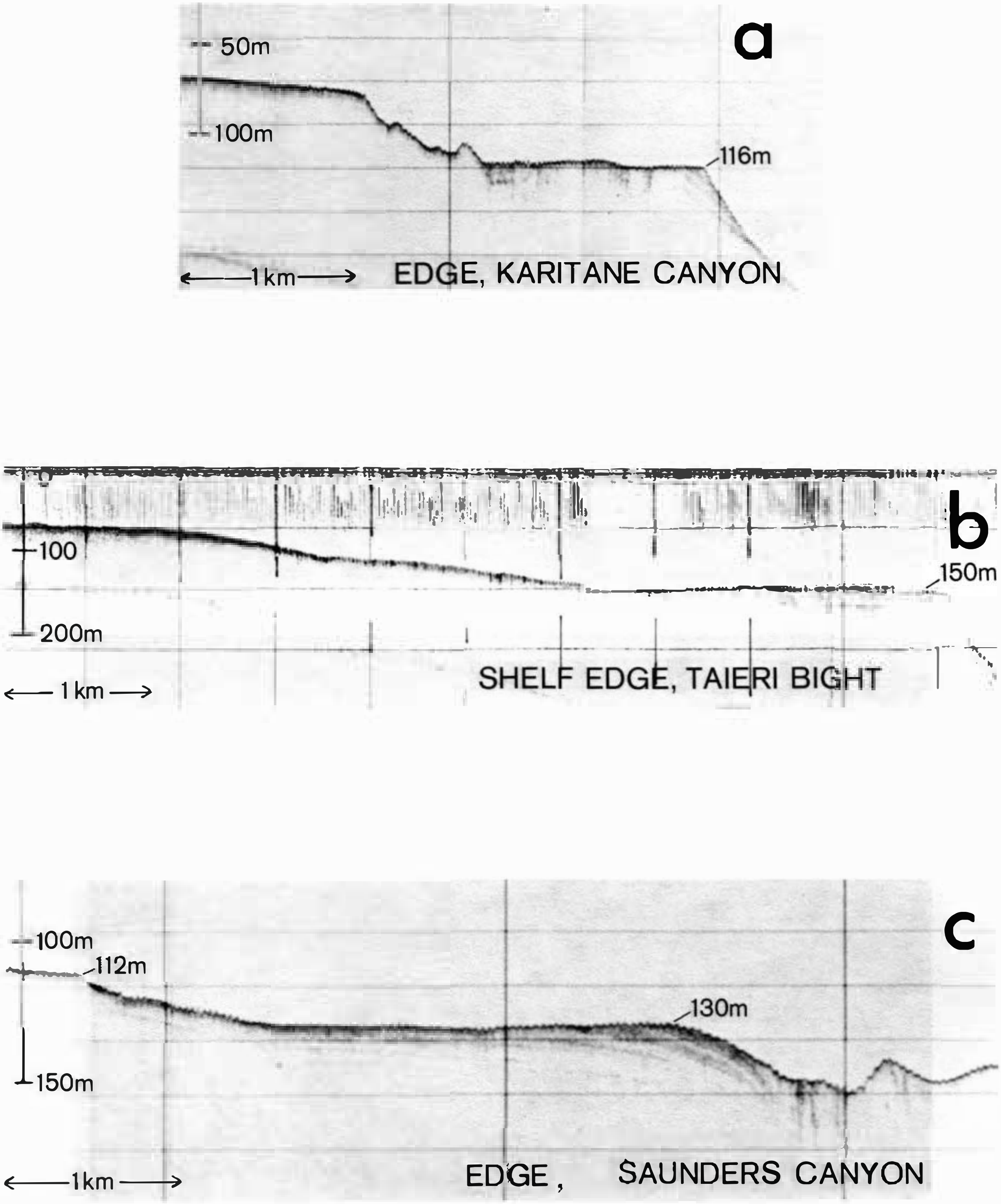


FIG. 15. 3.5 kHz seismic profiles of the terraces cut in the shelf edge near the submarine canyons off the Otago Peninsula (terraces in (b) and (c) have exaggerated widths due to a slowing down and course changes of the ship at the end of each seismic line). Note the presence of probable submerged shorelines at c.112 m, c.130 m, and c.150 m. The deepest feature is eroded and generally lacks sediment cover, suggesting either it considerably predates the latest (post-glacial) transgression or it is actively being eroded by modern currents.

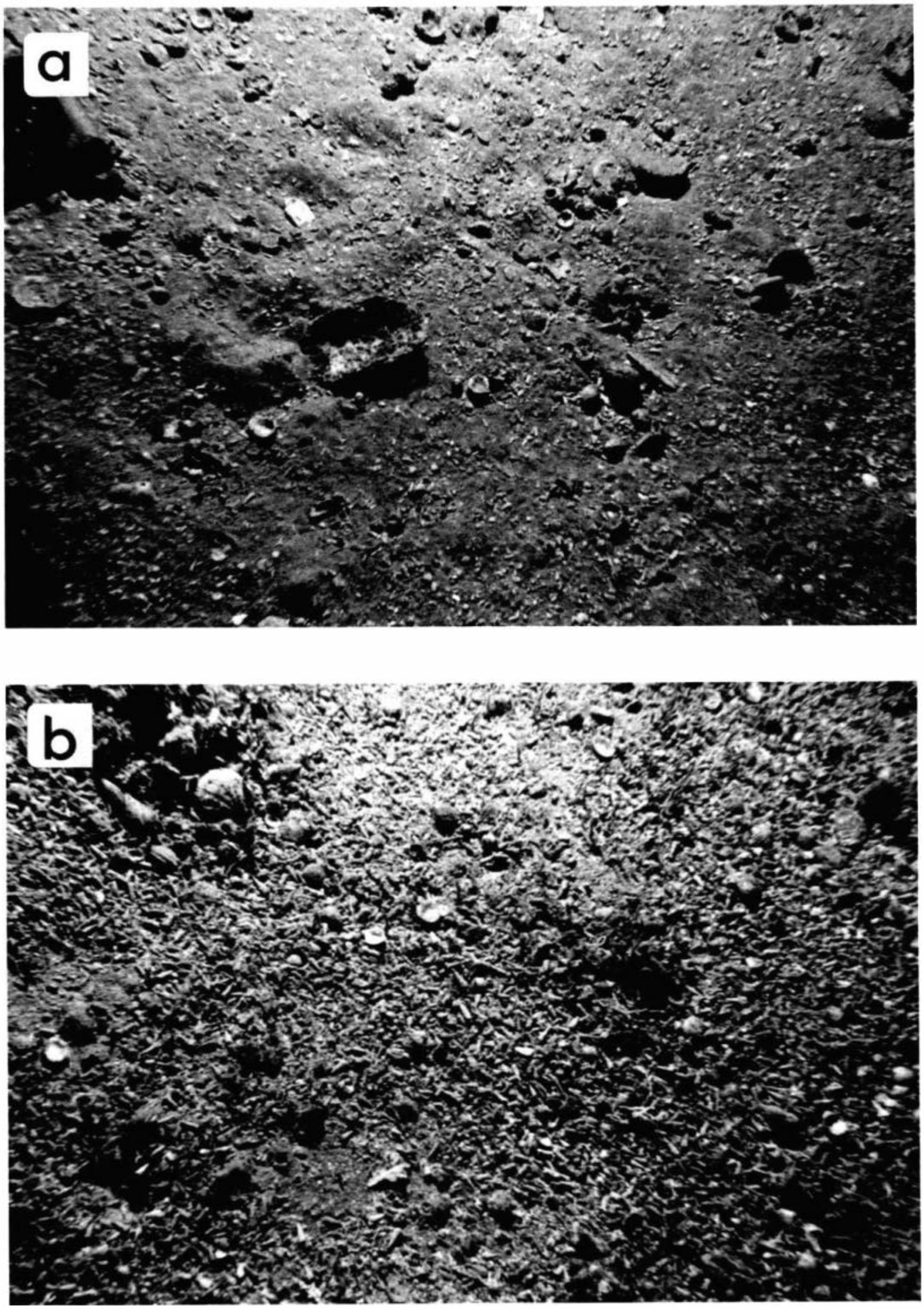
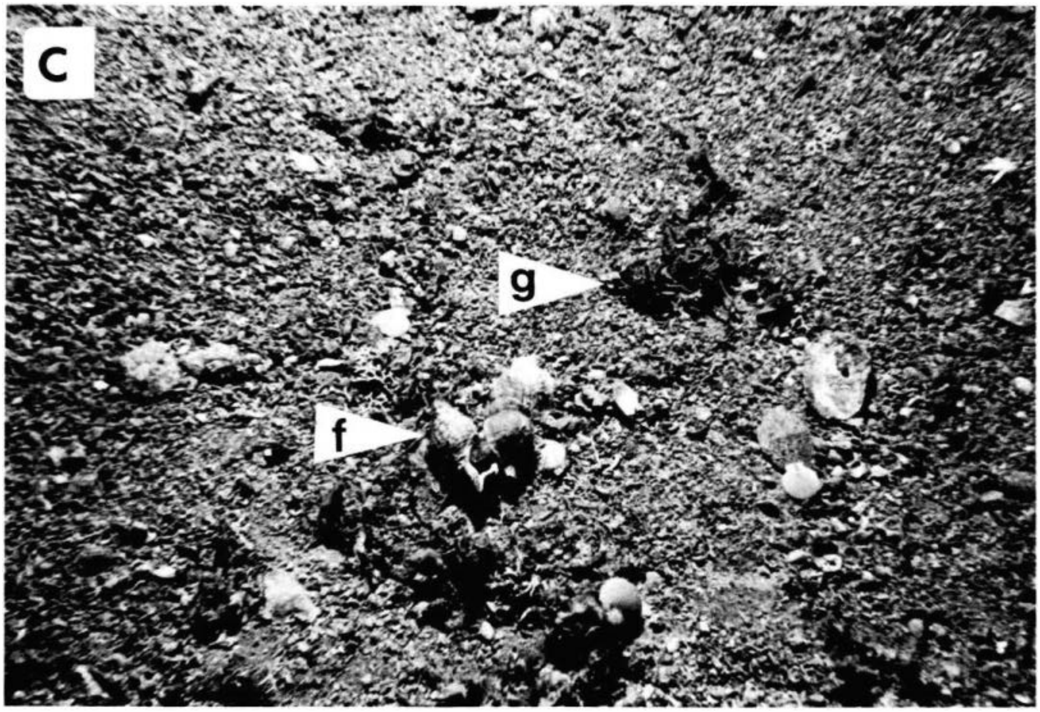
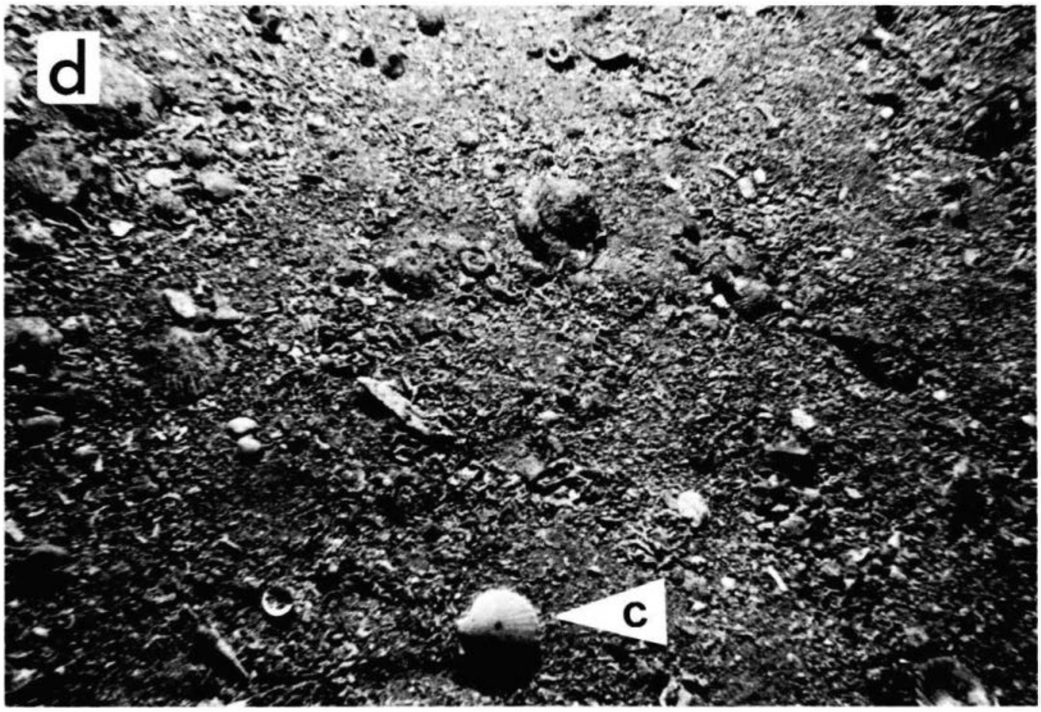


FIG. 16(*above and opposite*). Bottom photographs on the −110 to −120 m terrace cut in the shelf edge at the head of Karitane Canyon (compass is 8 cm on a side). (a, b) Station Q259, depth 113 m, on the north side of the canyon. *Stiracolpus* gravel, probably of lag origin. Scattered dead shells, often bryozoan encrusted, include *Mesopeplum*, *Venericardium*, *Panopea*, *Cardita*, *Chlamys delicatula* and lunulitiform bryozoa. (c, d) Station Q260, depth 120 m, on the south side of the canyon. Bryozoan (*Filicea*) shell gravel, probably of lag origin. Note live *Goniocidaris* (g), mating(?) *Fusitriton* (f) and *Chlamys delicatula* (c).





Plurigens phenax (Fig. 16). The latter species is of special interest, since its common occurrence in canyon faunas has led to its identification as a deep-water species (e.g., Dell 1956). In fact, *Plurigens phenax* is closely related, and probably conspecific with, *Tawera mawsoni* (Hedley), a cold-water species only known living from shallow marine situations in the subantarctic islands south of New Zealand (P. Luckens, pers. comm.). *Plurigens* is associated with deposits of the peak last glacial shoreline as far north as the Kaikoura coast, and the dead shells retrieved from deep water along the eastern South Island, including the holotype, are probably relict.

Other Relict Features

At times when the shoreline was situated east of its present position, the Otago rivers must have traversed the continental shelf before debouching into the sea at lower elevations than their present mouths. The rivers would therefore have incised themselves into any earlier interglacial deposits or bedrock, even assuming no relative uplift of the Otago shelf.

3.5 kHz seismic profiles of the inner to middle shelf off Karitane reveal buried river channels beneath a thin veneer of modern sediment. The channels are incised into folded Cenozoic rocks, and are up to 40 m deep and 1 km wide (Fig. 17). Though the zone of channels can be traced across several lines, the strong acoustically reflective nature of the relict sand of the middle to outer shelf prevents sufficient penetration to allow the channels to be traced out to the shelf edge.

From their position and depth of incision the channels probably relate to the shoreline at − 110 m, that of the last glacial lowstand. They contain a stratified sedimentary fill, presumably a fluvial aggradational facies, deposited as sea level rose towards its modern position. That the channels are developed in bedrock implies the prior removal of earlier interglacial deposits, which would be consistent with active uplift of this sector of shelf.

Biogenic sand/gravel facies

Much of the outer shelf is mantled by biogenic calcareous sand and gravel. Widely-spaced samples suggest the mantle is fairly uniform, but when viewed in detail using camera transects and side-scan sonographs, the distribution patterns are often highly localised with individual patches or belts of sediment sometimes only a few tens of metres across. Thus, while regional maps of sediment distribution are useful as broad perspectives, they lie far from the reality of the detailed situation. For this reason the following discussion is based on data gathered from small areas where we have close control.

Biogenic Sand

Large areas of the shelf beyond the 90 m isobath (Fig. 4) are mantled with medium to coarse sand consisting of minute bivalves and foraminifera, together with locally abundant bryozoan and large molluscan fragments (Fig. 16; cf. Andrews 1973; Williams 1979). Sorting values are generally poor on account of an ubiquitous biogenic gravel content, typically in the range of 10–25% (Fig. 5). The shoreward edge of the biogenic facies belt grades into the relict gravel and relict/palimpsest sand facies. As a result, the boundary between the facies is arbitrarily placed at a line where sediment carbonate content exceeds terrigenous content.

Samples and sonographs (Fig. 18a–c) show that the biogenic sand forms part of a patchy, northward-moving sediment cover on the outer shelf. Here ribbons up to 200 m wide are aligned along the shelf isobaths. Unfortunately, low sample density prevents identification of ribbon components. Furthermore, ribbons are too thin to show on seismic profiles, and are, therefore, inferred to be at most a few tens of centimetres thick, similar to sand ribbons elsewhere (*see*, e.g., Belderson *et al*. 1972; Kenyon and Stride 1970). Some ribbons contain transverse dunes normal to their margins, with spacing between dune crests of about 4 m. The ribbons are most conspicuous at depths of 70–90 m, some 6 km seawards of the Saunders Ridges; further seawards they merge in places to form a more continuous cover.

The preferred development of the ribbons near the Otago Peninsula is not coincidental. As with the inner to middle shelf sand waves, the relatively rapid flow around the Peninsula has probably been an important factor in ribbon development. Again the calm weather flow appears too weak to generate ribbons (cf. Kenyon 1970), so the flow must be reinforced periodically by motions associated with the passage of southerly storms (*see*, e.g., Newton *et al*. 1973).

Biohermal Deposits

Bryozoan fragments are widespread in all sediments on the middle and outer shelf, and it has long been appreciated that *in situ* growth of bryozoa occurs on the outer shelf off the Otago Peninsula (*see*, e.g., Andrews 1973; Probert *et al*. 1979). This is the zone of maximum bryozoan abundance; the *in situ* forms being scarce both north (Loutit 1975) and south (Williams 1979) of the Peninsula.

The bryozoa are distributed in two separate belts. The inner belt is dominated by the branching *Cinctipora elegans* Hutton, which attaches preferentially to the pebbles from the relict gravels. The outer belt is dominated by *Cellaria immersa*, *Celleporaria* sp., and in particular by *Hippomenella vellicata*, and occupies the outermost shelf and upper slope at depths of 120—200+ m.

On the seismic records the bryozoan beds form a thin veneer above a reflector which, when traced south, passes beneath the Saunders Ridges. Piston core P152 penetrated to this reflector, the *Chione*-bearing estuarine mud referred to earlier. Replicate box-cores and piston core P153 (Fig. 8) show that the bryozoan beds are developed on a thin, muddy, gravel layer which contains terrigenous pebbles identical to those from the Saunders Ridges further south. Recalling the 12,000-year age of the underlying estuarine silts, it is apparent that either the shelf east of the Peninsula was the site of non-deposition during the time of the Saunders Ridges shoreline, and/or that any sediments

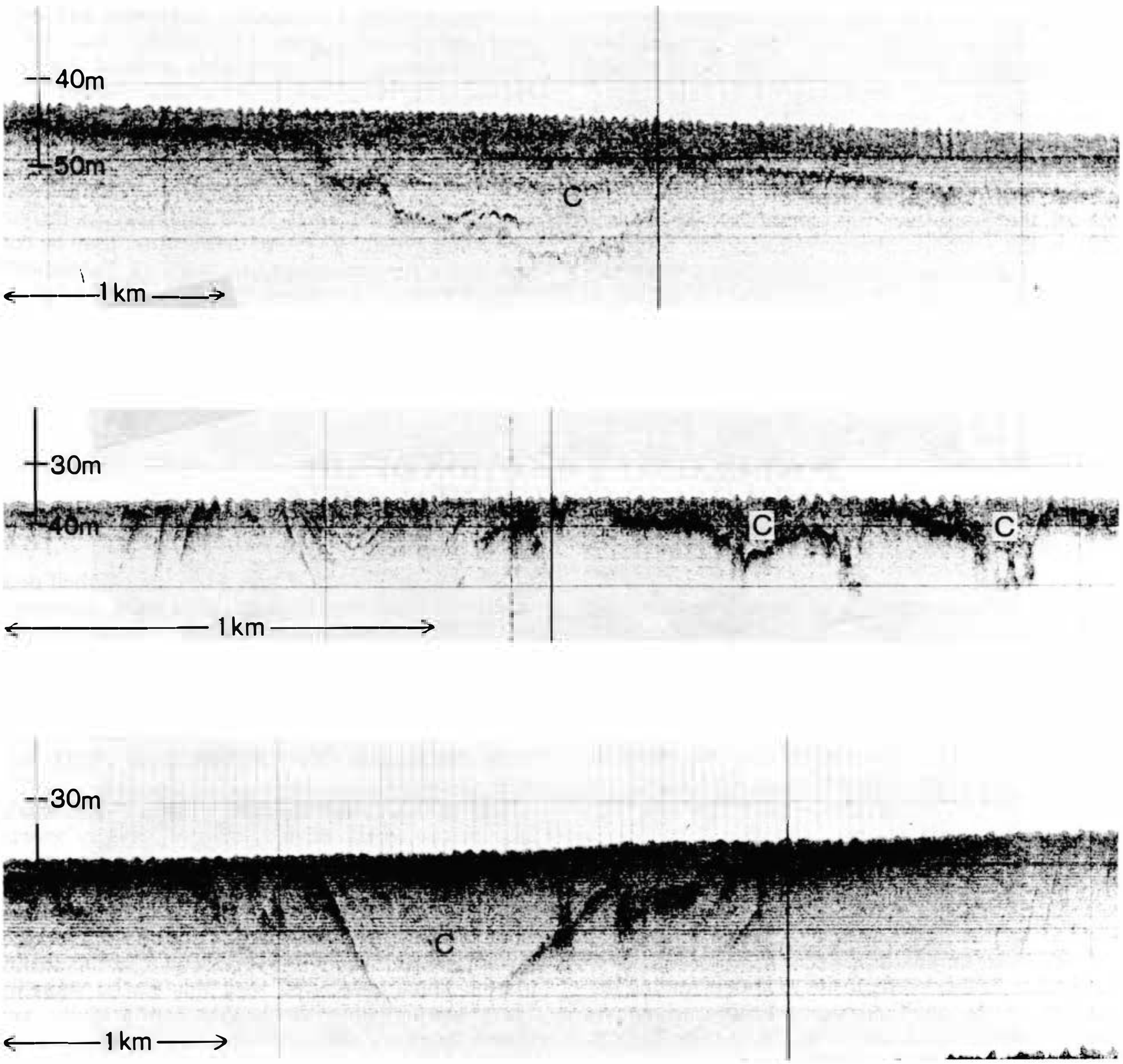


FIG. 17. 3.5 kHz seismic profiles from the inner shelf off Karitane. Infilled channels (c) and other depressions within the Cenozoic "basement" beneath the Holocene sand wedge.

deposited east of the Peninsula during the lifetime of the Saunders Ridges shoreline have subsequently been eroded. Given the volume of sediment associated with the ridges and with similar middle shelf shoreline deposits elsewhere off the eastern South Island (*see*, e.g., Herzer 1981; Carter *et al.* 1982; Carter and Carter 1982), erosion seems more likely. Certainly there is sufficient power in the flow off the Peninsula to instigate transport of sandy bedload, in which case the thin veneer overlying the estuarine mud could reasonably be regarded as a lag deposit — the product of unmixing (cf. Swift *et al.* 1971).

The bryozoa themselves occur as discrete clumps up to about 0.5 m diameter, separated by a substrate of poorly sorted muddy and sandy shell-rich sediment (Figs 16b, 19). The associated macrofauna is rich in epifaunal species, notably molluscs and ascidians, which nestle amongst the bryozoa together with the ophiuroids *Ophiactis* and *Pectinura*. Concentration of these bryozoan beds on the shelf off the Otago Peninsula suggests they are responding mainly to favourable physical oceanographic conditions, in particular the acceleration of the flow as it rounds the promontory (cf. Andrews 1973; Probert *et al.* 1979).

The outer bryozoan belt, though best developed off the Otago Peninsula, is associated with a rich epifaunal shell gravel community which also occurs on the outer shelf and upper slope in areas north and south of the Peninsula. First described by Powell (1950) as the *Chlamys delicatula-Fusitriton* community, this faunal grouping also includes as common elements *Sclerasterias mollis*, *Goniocidaris umbraculum*, brachiopods (*Magasella*, *Neothyris*), and other species of outer shelf group 4A of Probert *et al.* (1979). The association occurs over wide areas of the outer shelf as extremely poorly sorted calcirudites composed of a mixture of living, recently dead, and long dead shells; some common genera, such as *Panopea*, have not been collected alive and may be relict forms. Even if relict material is present, this characteristic and profuse outer shelf fauna represents a thriving modern community, whose distribution may be controlled by the colder temperatures of Subantarctic Surface Water, which here bathes the shelf edge.

POST-GLACIAL EVOLUTION OF THE SOUTH OTAGO CONTINENTAL SHELF

Sea-level Model

An accurate interpretation of the sedimentary and faunal features of the South Otago shelf can only be made against a knowledge of the behaviour of sea level over the last 20,000 years. The best available estimates indicate that the sea transgressed rapidly from a peak last-glacial shoreline at about − 110 m (18,000–20,000 years B.P.), to stabilise at new shorelines at about − 75 m (15,000 years B.P.), and − 55 m (12,000 years B.P.). Further rapid transgression followed with successive shorelines briefly stable at − 30 m (9,000 years B.P.) and − 12 m (7,500 years B.P.). Modern sea level was attained at c.6,500 years B.P., since when no major fluctuations have occurred (Gibb 1979; Herzer 1981).

In addition to an adequate model of sea-level behaviour, a further prerequisite to understanding the evolution of the shelf is comprehensive core-controlled, high-resolution seismic profiling data. Though we have only scattered 3.5 kHz seismic profiles and cores, and though our sea-level model is rudimentary, sufficient data are to hand to allow explanation of the major features of South Otago shelf sedimentology.

Peak Last-Glacial Shoreline

During the last glaciation, at c.18,000–20,000 years B.P., the shoreline was situated at the shelf break. Rivers incised into Tertiary and older Quaternary shelf sediment as they flowed eastwards to deposit their load more or less directly into the Otago canyons and hence to the Bounty Trough. Cores from the off-shelf depocentres indicate the rivers carried a preponderance of glacial-derived suspended load which accumulated to form a distinctive blue-grey, micaceous mud with a low, but characteristic biogenic component of radiolaria and other siliceous organisms (Griggs *et al.* 1983). This type of sediment continued to dominate slope and canyon sedimentation up to 13,000 years B.P..

During this maximum lowering of sea level, marine erosion caused the development of a gently seaward sloping platform, cliffed on its shoreward side, against which littoral and shallow marine facies accumulated as a terrigenous sedimentary wedge (cf. Fig. 15). Cold-water molluscs such as *Plurigens* and *Tawera spissa* phenotype *subsulcata* are represented in the shallow marine fauna associated with this glacial shoreline. These faunal elements, together with gravelly, well-sorted sands, are preserved today in numerous places on the outer shelf and upper slope, where they may be intermixed with minor amounts of modern mud, or large amounts of modern biogenic material of the outer shelf bryozoan-*Chlamys* community.

Middle and Outer Shelf Shorelines

After a rapid transgression, the shoreline stabilised at around − 75 m approximately 15,000 years B.P.. A sediment wedge developed against the shoreline, at least off Molyneux and Blueskin Bays, while further north, off Banks Peninsula, intense reworking of the

FIG. 18(*opposite*). Side-scan sonographs of sand ribbon terrain on the outer shelf. Ignore artefacts (arrowed) due to print failure, surface reflections and oblique paper creases. (a) Westerly (inshore) edge of ribbon field, just seawards of the outer Saunders Ridge in depths of 60–70 m. Mobile sand above dunes of relict gravel (dark). (b) Ribbons of mobile sand, some with transverse dunes, and linear zones of bryozoan colonisation (bb), above relict sand (dark). (c) Easterly (offshore) edge of ribbon field on outer shelf. Mobile sand ribbons with conspicuous transverse dunes above relict sand or gravel (dark).

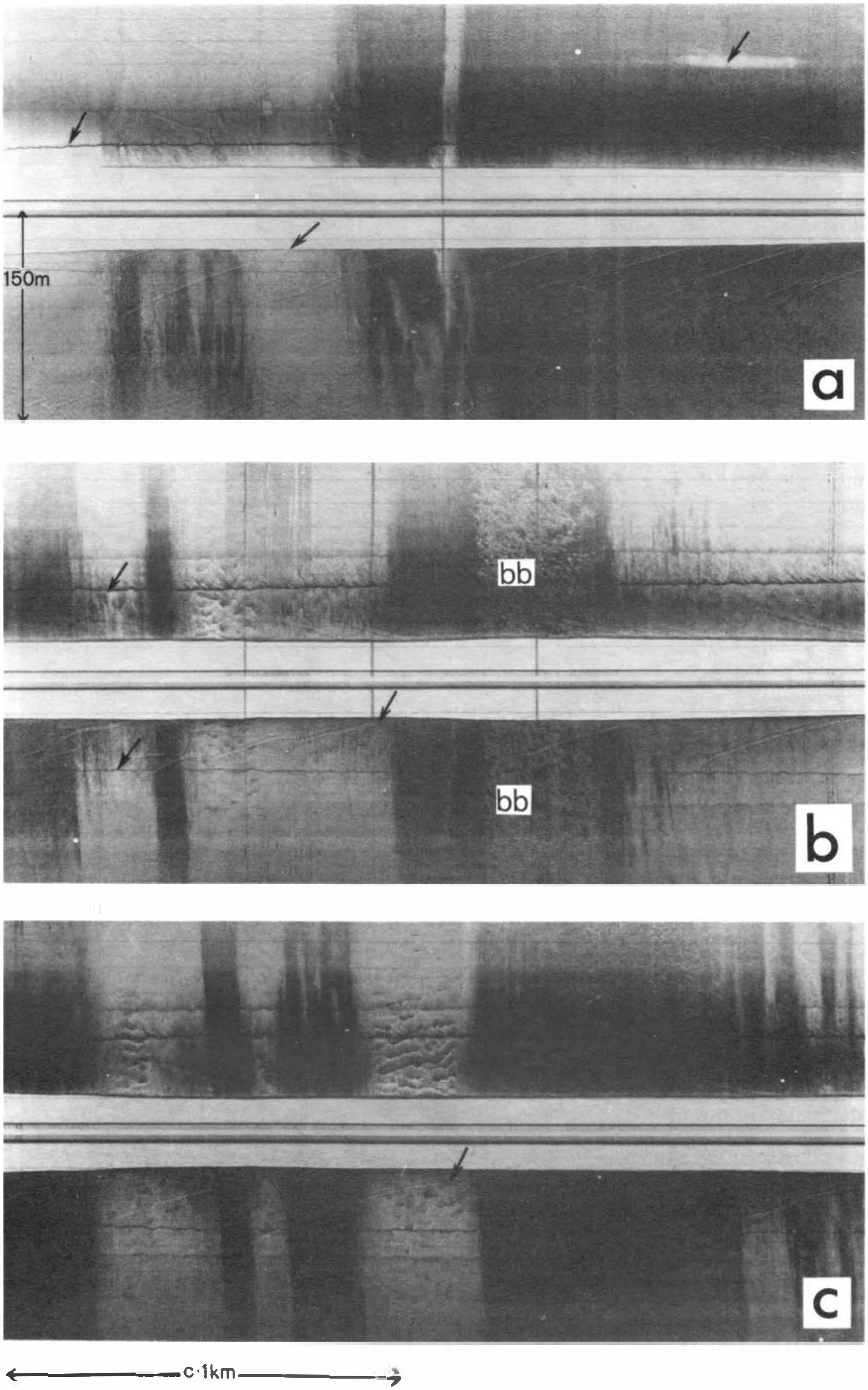

150m
a
bb
bb
b
c
c·1km

FIG. 19. Bottom photographs of the bryozoan beds on the middle to outer shelf east of the Otago Peninsula. Station Q258, depth 84 m. The beds consist of discrete clumps of living bryozoa (19a) separated by a varied substrate of muddy sand and shell gravel (19b). Ophiuroids and actinarians are conspicuous components of the living benthos.

seabed produced shallow-water shoals containing the intertidal mollusc *Paphies* (Herzer 1981). Sea level then rose rapidly once again and stabilised at around − 55 m, 12,000 years B.P..

Judging from the large volume of terrigenous sediment built against the resultant shoreline, both off Otago and Canterbury (Carter *et al.* 1982), the shoreline was stable or slightly regressive at these mid-shelf depths for an appreciable period of time, perhaps as long as several thousand years. The Clutha River, fed by melting glaciers, was the major contributor of sediment to the 12,000-year shoreline in Otago. Coarse-grained bedload deposits were worked northwards alongshore to form the Saunders Ridges, behind and amongst which accumulated finer-grained estuarine deposits. The gravel bands extended as far north as the Otago Peninsula and perhaps some distance further, defining a shoreface against which accumulated a typical seawards-fining wedge of sand and silty sand, now preserved widely on the middle and outer shelf as relict and palimpsest sediment. Relict shells such as *Antisolarium* and *Umbonium* are widespread, but the cold-water forms typical of the 18,000–20,000-year shoreline have disappeared, which is consistent with an ameliorating climate and probably with changing oceanographic conditions. This change from cold to warm conditions appears to have been quite abrupt since the boundary between glacial and interglacial muds on the Otago slope and within the Bounty Trough is sharply defined by lithology and microfauna (Griggs *et al.* 1983).

Inner Shelf and Modern Shorelines

With the rapid transgression of the shoreline again, the Saunders Ridges and their offshore sediment wedge were drowned *in situ*. The 9,000-year and 7,500-year shorelines reported by Gibb (1979) have not yet been recognised on the South Otago shelf, probably because of the blanketing effect of modern inshore sediment. However, some time during the movement of sea level from the Saunders Ridges shoreline to its present location, parts of the ridge gravel were moved inshore and north as a thin, reworked blanket.

Since the arrival of the shoreline at the modern position, the Otago rivers, notably the Clutha, have been providing mainly sand-sized bedload to the shelf, where it has been entrained north-eastwards in the inner shelf transport regime and now forms the modern terrigenous sand wedge. Where this drift system passes shoreline promontories, sand accumulates along the shelf as a submerged spit, as off Cape Saunders. Elsewhere, where the flow is strong, fields of sand waves and dunes have developed. Meanwhile, suspended load from the rivers is mainly transported north-east, eventually to be deposited in a series of depocentres on the upcurrent side of major promontories and in the Bounty and Hikurangi Troughs (Carter *et al.* 1982).

Beyond the outer edge of the modern sand wedge, the relict deposits of the middle and outer shelf have been subjected to the modifying effects of modern currents. Winnowing occurring east of the Otago Peninsula has resulted in the development of a lag gravel on which the inner *Cinctipora*-dominated bryozoan beds occur. Further south the upper layers of the Saunders Ridge gravels have been modified by the modern southerly swell and, offshore from the Saunders Ridges, sand ribbons and blankets of modern bioclastic sand are moved north-eastwards by the mean flow and tides reinforced by storm-induced motions.

SUMMARY

1. Four major sediment facies are recognised on the South Otago shelf: a modern terrigenous sand facies on the inner shelf; a relict terrigenous gravel facies on the middle shelf; a relict/palimpsest sand facies on the middle shelf, but also located near the shelf break; and a biogenic sand/gravel facies covering the outer shelf (Fig. 20).

2. The modern terrigenous sand facies has accumulated since the sea reached modern levels c.6,500 years B.P.. Areas of mud deposition, submerged longshore bars, sand wave and dune fields all occur within this facies, and are features created by, and in equilibrium with, the modern flow regime.

3. The relict terrigenous gravel facies at − 55 m accumulated mainly about 12,000 years B.P., when the shoreline was sufficiently stable to form nearshore gravel ridges and associated estuarine deposits.

4. Terrigenous sand of the relict/palimpsest sand facies has probably been "unmixed" from the relict terrigenous gravel facies, as well as being related to prominent old shoreline deposits at − 55 m (12,000 years B.P.), − 75 m (15,000 years B.P.), and − 110 m (18,000–20,000 years B.P.).

5. Biogenic sediments on the middle and outer shelf are a mixed assemblage of relict and reworked relict shells and modern living genera. The common occurrence of dead *Umbonium*, *Antisolarium*, *Zeacolpus* and *Tawera spissa* in middle and outer shelf sandy

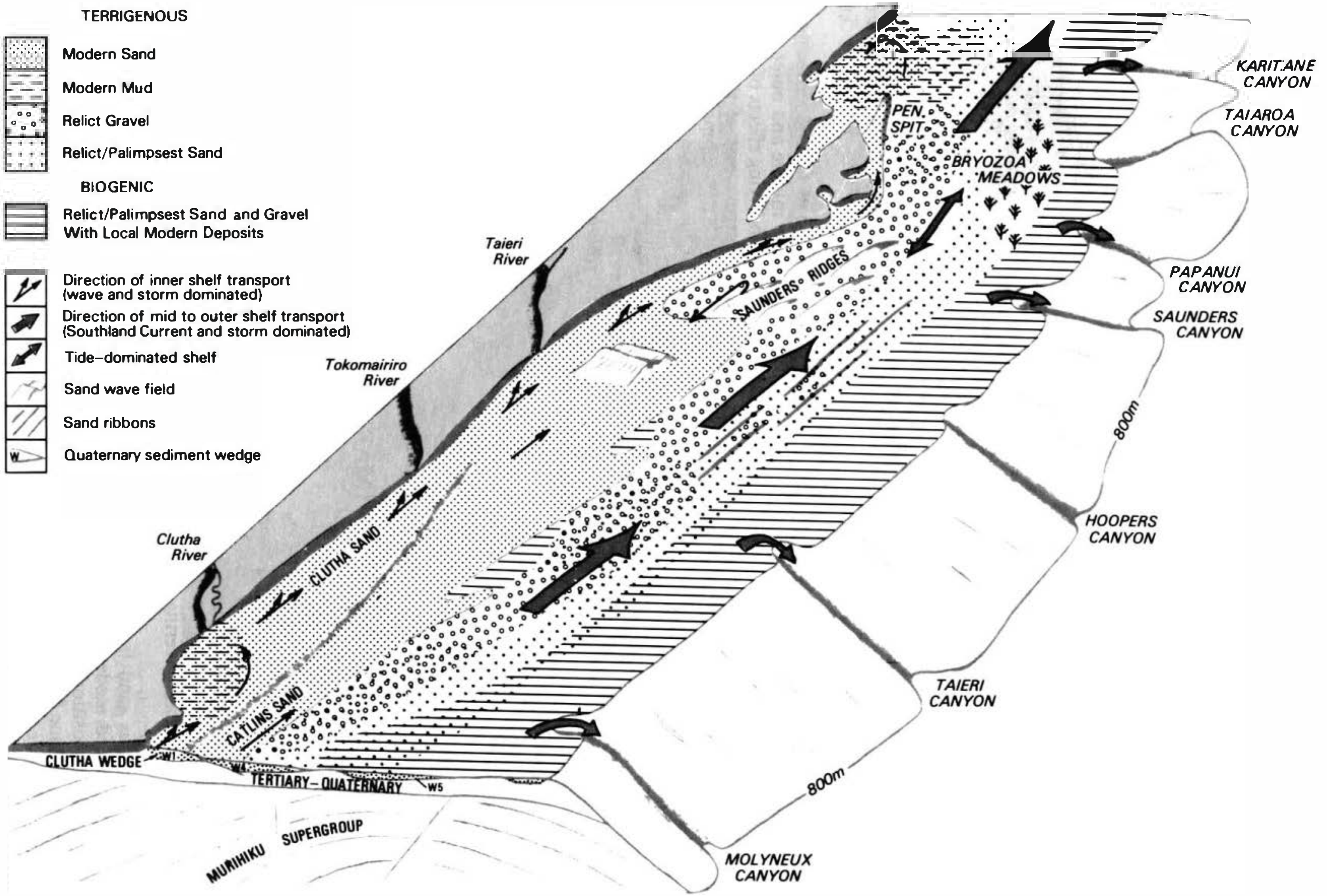


FIG. 20. Schematic rendition of the hydraulic and sedimentary regimes operating on the South Otago continental shelf and upper slope.

gravel are relict, because the two former species are preserved well below their normal depth range, and the two latter species usually live in silty or muddy substrates.

6. Modern shelf faunal assemblages comprise a mainly molluscan-dominated fauna in nearshore terrigenous sands (*Umbonium*) and muddy sands (*Antisolarium, Nucula, Zeacolpus, Tawera, Myadora*); a sparse *Pectinura-Chloeia*-actinarian fauna on the mid-shelf relict terrigenous gravel; and two bryozoan-dominated assemblages on the middle to outer shelf — the inner assemblage characterised by *Cinctipora*, the outer assemblage by *Hippomenella* and the bivalve, *Chlamys delicatula*.

7. The shelf has evolved to its present state in a series of discrete steps controlled by the post-glacial behaviour of sea level and the evolution of the modern hydraulic regime. Some aspects of the sedimentology, notably the inner shelf terrigenous sediment wedge, have been built in equilibrium with present processes; other features, notably the Saunders Ridges and other offshore relict features, essentially represent a little-modified, drowned seascape and are not in equilibrium with present processes. Modern faunal assemblages, however, have developed right across the shelf on all these facies, and are in ecological equilibrium with the substrate and hydrology present at different sites.

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