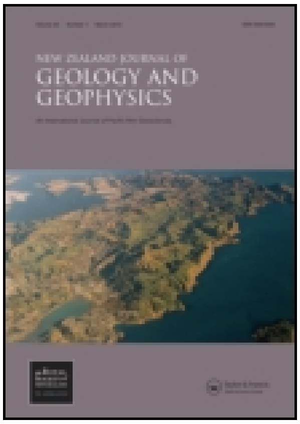

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Holocene evolution of the nearshore sand wedge,South Otago continental shelf, New Zealand

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Abstract The 85 km long, inner–middle continental shelf off South Otago, is mantled by a nearshore sand wedge. High resolution seismic profiles show that this feature is most developed in Molyneux Bay, where a combination of sheltered water and abundant sediment supply, chiefly from the Clutha River, have encouraged deposition of up to 34 m of Holocene sediment.

The wedge appears to have evolved in two main stages. In the early Holocene, a lower wedge, W3, formed against a shoreline which is tentatively correlated with a −27 to −24 m stillstand between 9600 and 8800 years ago. W3 initially prograded across the floor of Molyneux Bay to the open shelf, where currents redirected sediment northeastwards. Wedge accumulation diminished with resumption of the Holocene transgression. When sea level stabilised at its present position 6500 years ago, the second stage commenced with deposition of modern sand, W1, over the lower wedge. Development was again influenced by shelf currents which controlled wedge morphology and redistributed sand 60 km along the middle shelf and 190 km along the littoral zone.

The lower wedge appears to have accumulated faster than its modern counterpart, presumably in response to enhanced sediment supply accompanying major changes in the early Holocene climate and oceanography.

Keywords continental shelf; sediments; nearshore sedimentation; sand wedges; transgression; sea levels; Holocene; Clutha River; Otago

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INTRODUCTION

The New Zealand postglacial transgression was punctuated by stillstands of sea level which were often accompanied by the construction of seaward-thinning, sedimentary wedges (Carter et al. 1982; 1986). The latest and perhaps best preserved example is the so-called "modern" sand wedge which has built seaward of the present shoreline since 6500 years B.P. (Gibb in press). In places, this sand wedge overlaps similar sediment bodies formed at lower stillstands (Carter et al. 1985). Such shoreface wedges and underlying basement are significant in that they comprise a record of the nature of the postglacial transgression on the continental shelf.

Generalised descriptions of the Holocene nearshore wedge are found in regional seismic studies of the New Zealand continental shelf by Lewis (1973), van der Linden & Norris (1974), and Norris (1978). However, because of inadequate resolution of the seismic systems used in these studies, few details exist on the stratigraphy and structure of the wedge.

Present study

This paper centres on a large sand wedge covering the inner–middle shelf off South Otago (Fig. 1). (The term **wedge**, as used here, includes the wedge-shaped body and the thin apron of sand at its seaward margin.)

The shelf between Nugget Point and Otago Peninsula is covered by 530 line kilometres of high resolution seismic profiles run with an EGG "Uniboom" system (CRA Exploration 1982). Most lines were run perpendicular to the coast at an average spacing of 4.9 km (Fig. 1). Additional information is provided by 3.5 kHz profiles, surficial sediment samples, and a few piston cores (see Carter et al. 1985), all of which are lodged at the New Zealand Oceanographic Institute.

The line density and excellent acoustic penetration of the "Uniboom" system provide insights into the structure of the sand wedge and its underlying basement. These data assist evaluation of (1) the evolution of the Otago inner–middle shelf since commencement of the Holocene about 10 000 years ago and (2) the character of the Holocene transgressive surface and pre-Holocene geology.

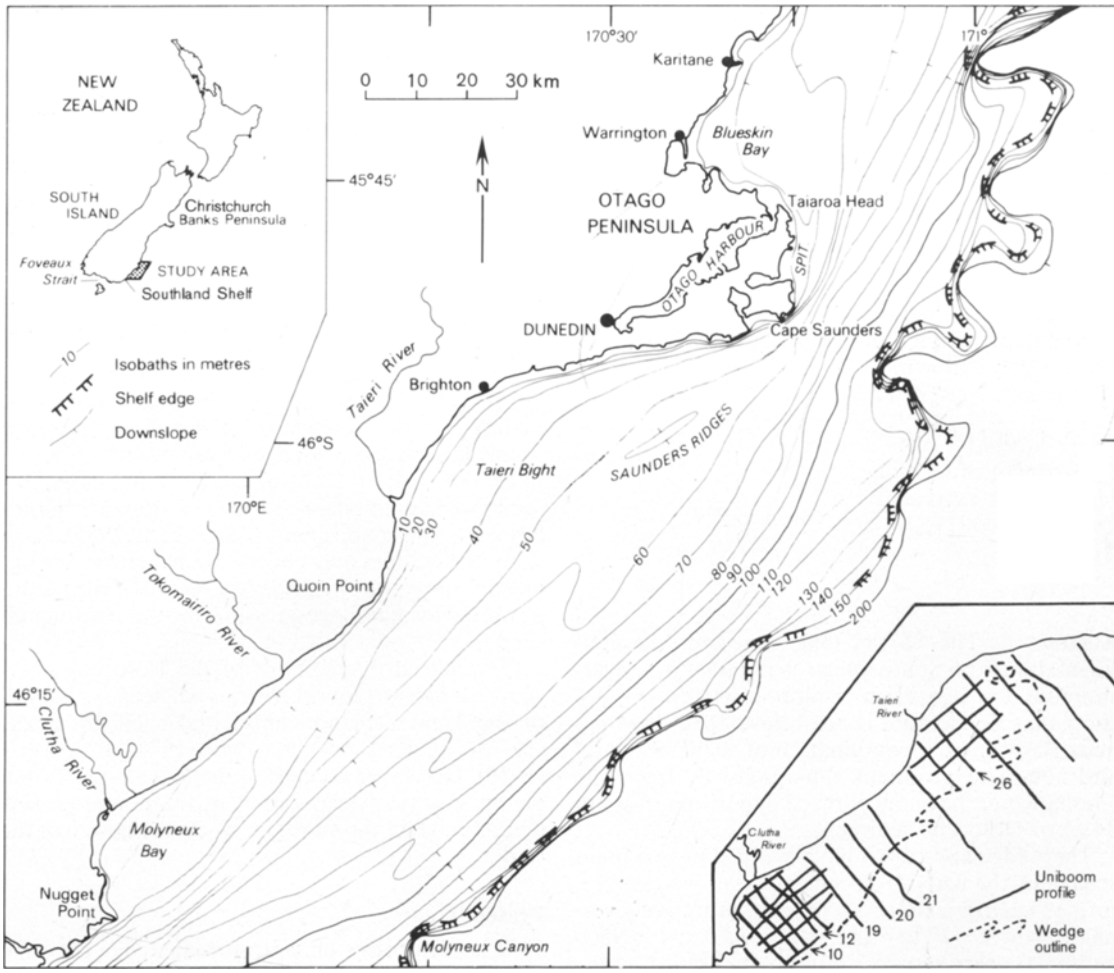

Fig. 1 Location chart (upper inset), metric bathymetry and positions of "Uniboom" seismic tracks (lower inset) of the Holocene wedge on the South Otago continental shelf. Numbered tracks are portrayed in following figures.

REGIONAL SETTING

The southern Otago shelf, between Nugget Point and Otago Peninsula, is 85 km long and averages 30 km width except off the peninsula where the width is reduced to 10 km. This low-relief shelf dips gently seaward to the shelf break located between 125 and 150 m depth (Fig. 1).

The shelf sediment cover has four distinct facies arranged in a succession of shore-parallel belts (Fig. 2) (Andrews 1973; Carter et al. 1985).

1. A modern sand facies, incorporating at least the upper parts of the sand wedge of this study, is restricted to a narrow belt on the inner shelf except in areas of high sediment input where the facies extends to middle shelf depths (30–70 m). The prevailing sediment is fine grey sand derived mainly from the Haast Schist terrane of the Clutha River catchment.

2. Iron-stained, quartzose granules and pebbles of a relict gravel facies cover the middle shelf. A well-defined relict fauna, drowned nearshore gravel ridges, and estuarine deposits dated at 12 150 years B.P. (^{14}C NZ4619) attest to the relict character of this facies.

3. A relict/palimpsest sand facies of the middle-outer shelf is a thin, mobile horizon of fine-medium sand containing a relict biogenic component and exhibiting active, current-induced bedforms.

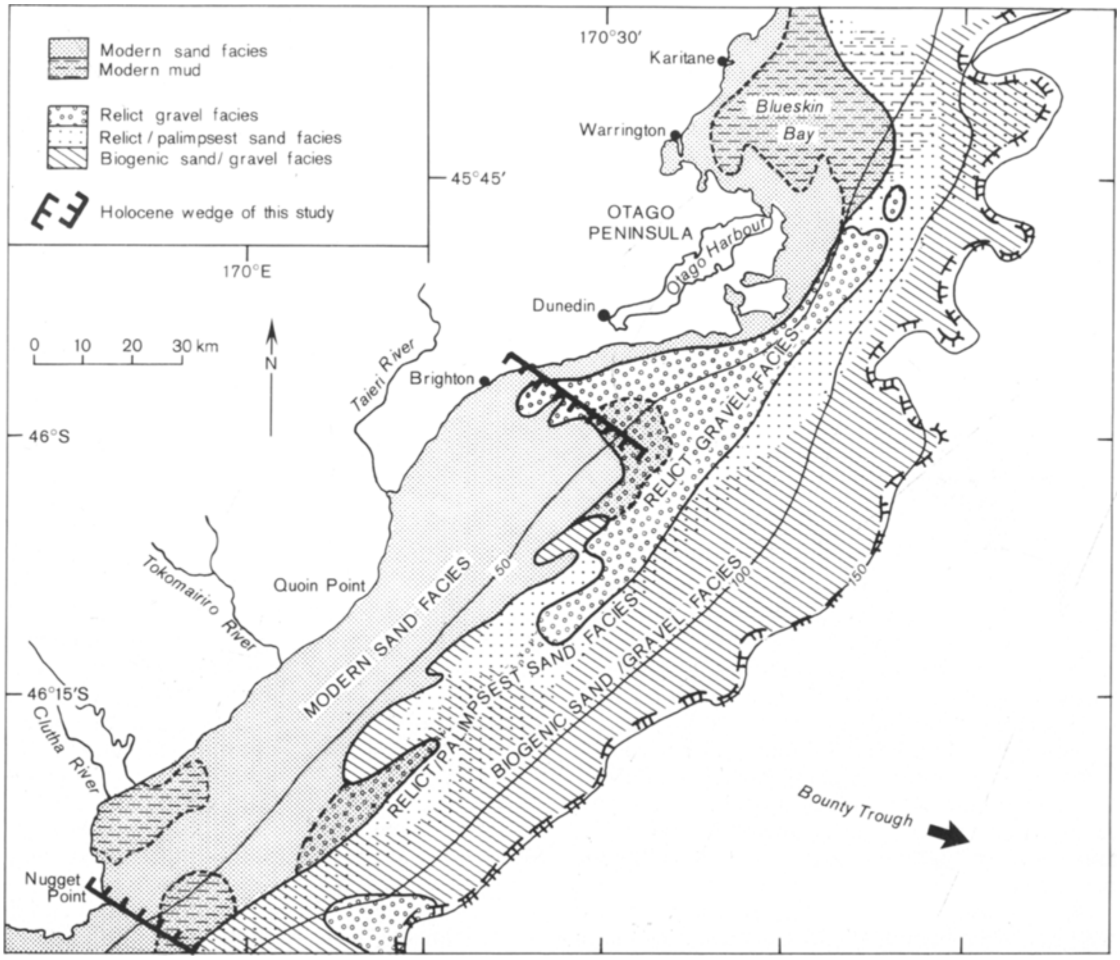

Fig. 2 Plan outline of the Holocene wedge with its modern sand mantle as determined from surficial sediment samples. Associated sediment facies are simplified from Carter et al. (1985).

4. A biogenic facies covers most of the outer shelf. Sediments are mainly molluscan- and bryozoan-derived sand and gravel of relict, palimpsest, and modern origins.

All facies have been modified by the modern hydraulic regime. A combination of southerly swell, the Southland Current, locally strong tides, and storm-induced currents has caused a net northeastward transport along the shelf (Andrews 1973; Bardsley 1972, 1977; Carter & Heath 1975). On the inner shelf, sand is probably transported daily, even in calm weather, whereas transport over deeper reaches of the shelf depends upon less frequent storm forcing of the shelf circulation (Carter & Herzer 1979).

Exceptions to the regional pattern occur off promontories such as Otago Peninsula where constriction of the mean and tidal flows raises their speed sufficiently to transport sediment on a daily basis at most shelf depths. Promontories also encourage deposition on their northern, upcurrent sides where fine sand and mud settle out from anticlockwise gyres in waters protected from the direct effects of southerly storm-forced currents.

WEDGE MORPHOLOGY

The upper surface of the sediment wedge is a terrace that is widest (18 km) in Molyneux Bay, directly off the Clutha River (Fig. 3). Here, the near-flat and featureless terrace extends 13 km seaward to the 30 m isobath where the slope steepens (0.5°) to form a terrace face which flattens out at around

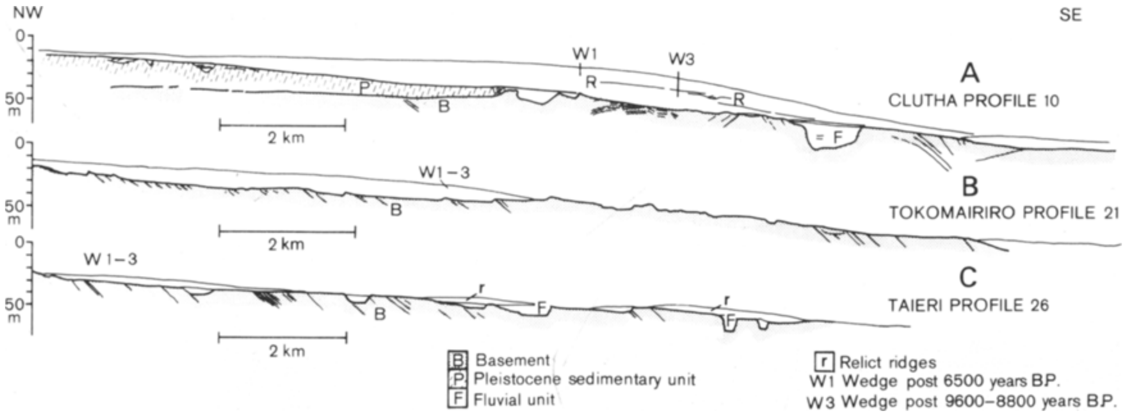

Fig. 3 Line interpretation of shore-normal profiles showing the principal seismic units of the Holocene wedge and substrate. For profile locations see Fig. 1.

90 m depth (Fig. 1). Off Nugget Point, the face is broken by a slight change in slope coincident with the 60 m isobath.

The terrace narrows markedly away from the Clutha River (Fig. 1, 3). Off the Tokomairiro River, the discernable top and face are 10.7 km wide, and in the north Taieri Bight are only 1–3 km wide.

Seaward of the terrace is a near-flat, thin apron of modern sand that widens progressively northeastwards to reach a maximum of 15 km in the north Taieri Bight (cf. Fig. 1, 2). Locally, the monotonous relief of the apron is disrupted by (1) areas of rough topography that presumably reflect the underlying basement rocks, (2) a succession of 10 m high, shore-parallel ridges (Fig. 3C), and (3) modern, current-induced bedforms (Carter et al. 1985).

SEISMIC STRUCTURE AND STRATIGRAPHY

High resolution seismic profiles exhibit five major stratigraphic units all of which directly or indirectly reveal the evolution of the wedge.

1. Basement

For much of its extent, the wedge rests unconformably on a rock basement. The structural attitude of this basement, comparison with the coastal geology (McKellar 1966), and a limited number of dredge hauls from submarine outcrops (New Zealand Oceanographic Institute stations P173, P176; commercial fish hauls, R.M. Carter pers. obs.) collectively indicate that the basement comprises sedimentary and metamorphic rocks of the Torlesse Supergroup, overlain by Cretaceous–Cenozoic sedimentary rocks.

The older rock suite occurs mainly on the innermost shelf and in southern Molyneux Bay. Here the rocks are massive to poorly bedded, folded, and faulted (Fig. 3A). Where exposed on the seabed, outcrops typically have a disorganised, rugged relief (Fig. 4A).

By contrast, the overlying Cretaceous–Cenozoic sequence on the inner–middle shelf, northeast of Molyneux Bay, is a less-deformed succession of well-bedded, sedimentary rocks that dip regularly seaward at around 3° (Fig. 3B, C, 4D). The up-dip terminations of acoustically reflective beds form a series of elevated mounds at the unconformity with the wedge (Fig. 4D). These mounds have up to 10 m relief and locally pierce the wedge to crop out on the seabed. Although they cannot be traced between profiles with confidence, these mounds probably represent shore-parallel, homoclinal ridges (i.e., parallel to the regional strike onshore; e.g., Harrington 1958).

2. Pleistocene sedimentary unit

Within Molyneux Bay, adjacent to the Clutha River mouth, the basement and wedge are separated by a 29 m thick sequence of essentially undeformed, nearly flat-lying sediments. Internal reflectors are discontinuous, parallel to hummocky, with several infilled channels and other cut-fill structures (Fig. 3A). The unit is confined laterally by what we consider to be the offshore extension of the present Clutha valley, whereas, to seaward, it terminates against a basement rise.

The contact with the overlying wedge is an incised planar surface that rises gradually landwards. When

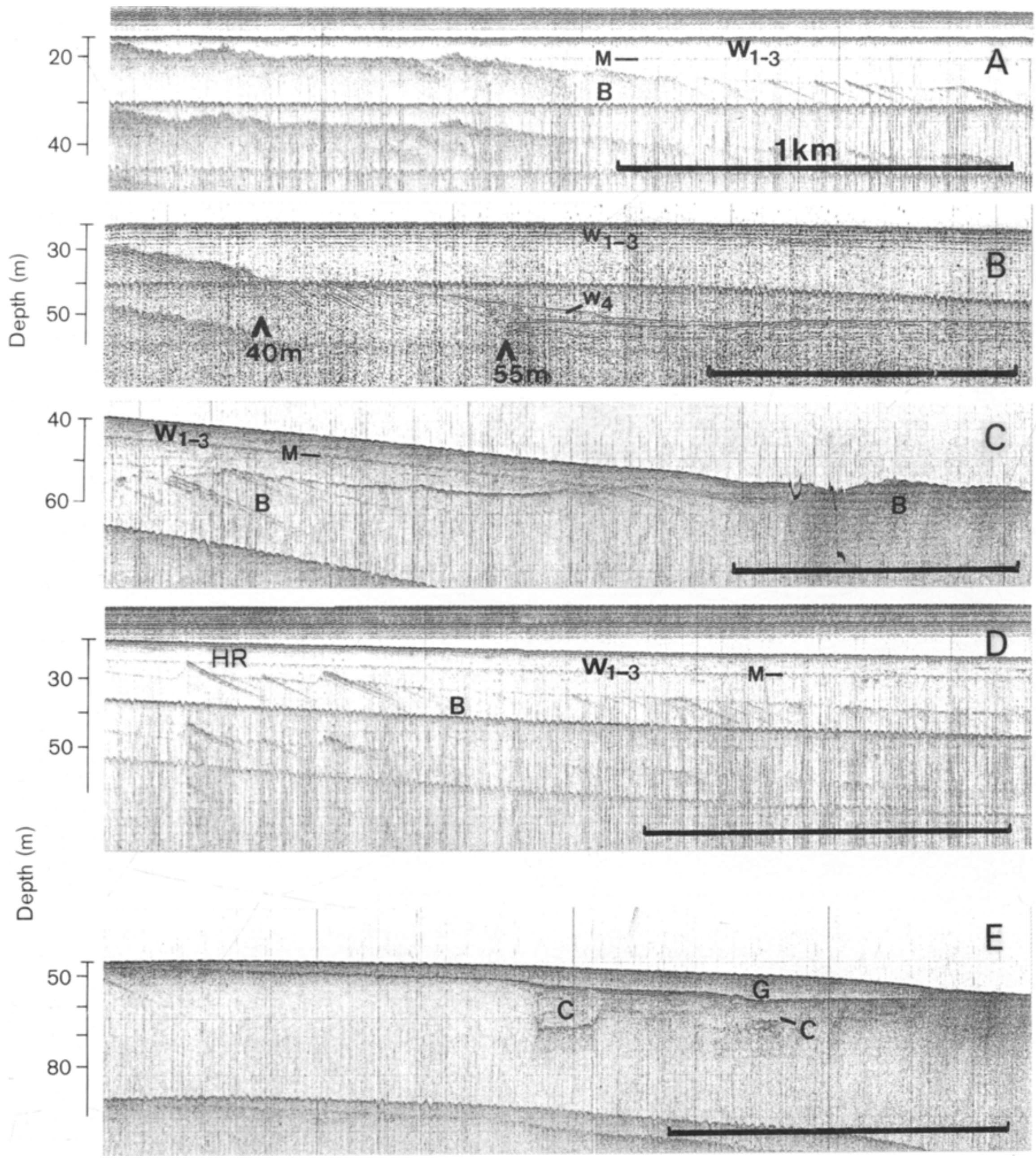

Fig. 4 Selected seismic sections (see Fig. 1 for locations) **A** *Profile 19* The −27 m deep platform cut into the basement (B) and overlain by undifferentiated Holocene sediment. M is a multiple. **B** *Profile 12* Undifferentiated Holocene (W1–W3) covering platforms −40 m and −55 m, the former having a small but well-defined wedge (W4). **C** *Profile 20* The Holocene wedge near the Tokomairiro River, where it terminates seaward against a basement high (B). Surficial sediment samples suggest at least part of the high has a veneer of modern sand. **D** *Profile 21* Detail of the Cretaceous–Cenozoic basement (B) with its seaward-dipping sedimentary rocks, the more resistant strata forming homoclinal ridges (HR). **E** *Profile 26* The distal reaches of the wedge in the Taieri Bight where it is reduced to a veneer covering relict gravels (G) of the Saunders Ridges, 12 150 years B.P., which in turn overlie buried channels (C) of the ancestral Taieri River.

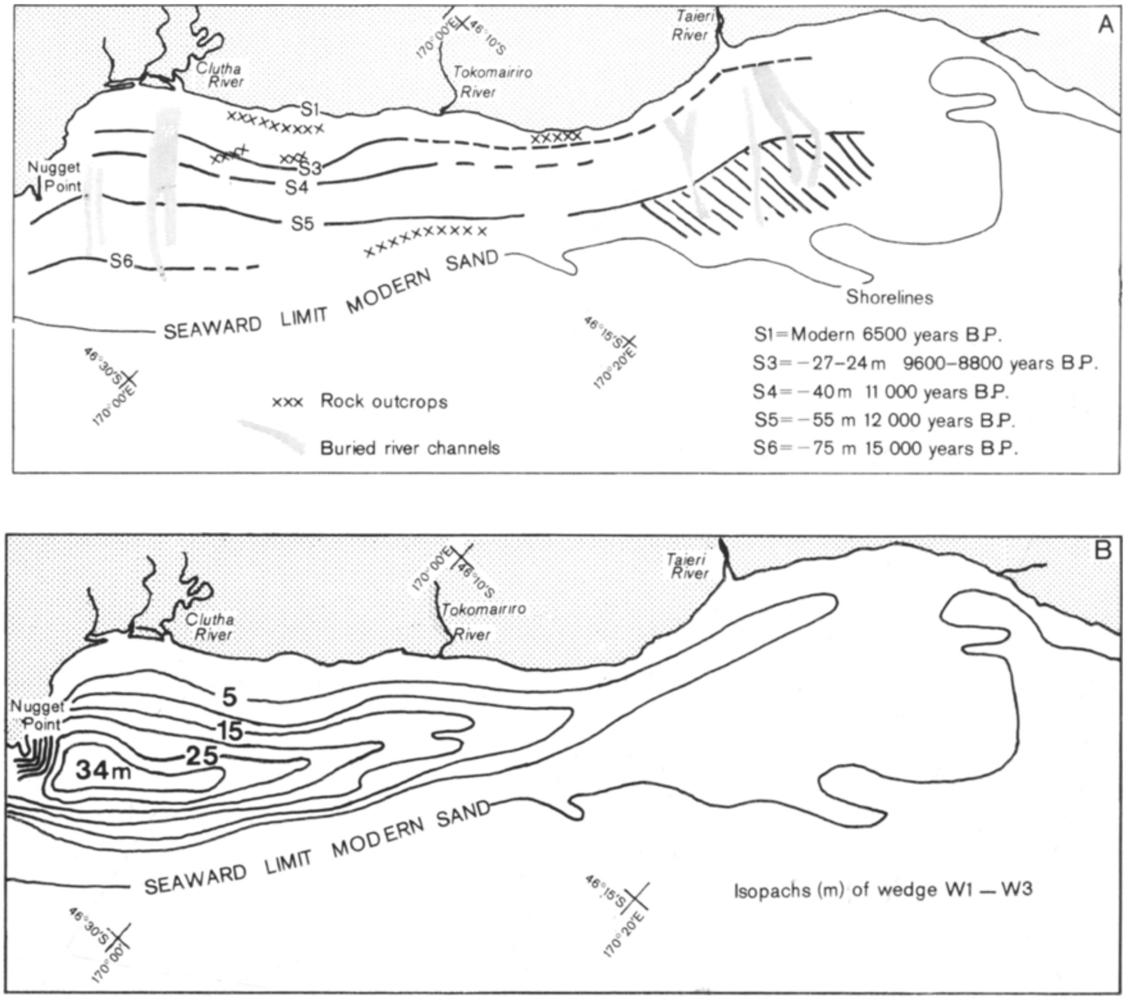

Fig. 5 **A** Location of postulated shorelines within and beneath the Holocene wedge together with basement outcrops and buried channels offshore from the present Clutha and Taieri Rivers. The hatched zone, associated with the 12 000 year old shoreline, represents an area of estuarine deposits associated with shoreface ridges (cf. Carter et al. 1985).
B Isopach map of the Holocene wedge with its major and minor depocentres off the Clutha and Taieri Rivers respectively. Areas where basement highs pierce the sediment cover are portrayed diagramatically on Fig. 5A.

projected onshore, this surface extends towards a coastal terrace suggesting these two features were once continuous. If so, we correlate the submarine beds with the terraced sediments which McKellar (1966) tentatively assigned to the last interglacial period, c. 125 000 years old.

3. Fluvial unit

The basement and Pleistocene sediments are incised by a number of channels, some over 1 km wide and up to 30 m deep (Fig. 4E, 5A). The sedimentary fill of the channels is generally weakly bedded, apart from a marked reflector which is co-planar with the erosion surface atop the channel walls. Similar features have been described from the shelf north of Otago Peninsula by Carter et al. (1985).

The largest channels are found seaward of the present Clutha River mouth, with others adjacent to the Taieri River and nearby streams (Fig. 5A). These features can be traced to the outer shelf but their extension to the shelf break or linkage with nearby submarine canyons have yet to be confirmed by seismic data.

The age of the channels cannot be determined with certainty, but those incised into the surface of the Pleistocene sedimentary unit (of assumed last interglacial age) were probably formed during the last glaciation when the rivers were graded to a base level at c. −114 m (Carter et al. 1986).

4. *Early postglacial transgressive unit*

The unconformity and associated sediment cover beneath the wedge represent the last postglacial transgression, the pre-Holocene phase of which occurred between 18 000 and 10 000 years ago as determined from radiocarbon dates and stratigraphic considerations (e.g., Carter et al. 1985; Herzer 1981).

The unconformity is bounded by a complex surface that reflects the basement geology and effects of the transgression. The latter is manifest as a series of erosional benches which Carter et al. (1985, 1986) interpret as wave-cut platforms formed at still-stands. Several platforms are associated with near-shore sediment ridges and wedges (e.g., Fig. 4B). Three such shorelines are recognised; at c. −75 m, c. −55 m and c. −40 m (Fig. 5A).

The −75 m shoreline was detected only off Nugget Point in the deepest water of the survey area. This feature appears as a wave-cut platform with a small mound (max. dimensions 1.5 km wide, 7 m thick) of sediment at the platform's edge.

The −55 m shoreline in Molyneux Bay is a well-developed platform that is locally disrupted by basement highs (Fig. 4B). In the Taieri Bight, this shoreline is associated with a major, drowned shoreface ridge complex, the Saunders Ridges. Seismic profiles (Fig. 4E) augmented by cores reveal these ridges to be mainly relict quartz gravel with a veneer of modern sand (the wedge apron of this study). The ridges rest on estuarine sediments of radiocarbon age 12 150 years B.P. (Carter et al. 1985).

Unlike its predecessors, the −40 m platform is inconspicuous and cannot always be traced between profiles. Where evident, the platform is c. 500 m wide and is sometimes associated with a small but well-defined wedge emanating over the −55 m platform (Fig. 4B). In the absence of dated samples, the −40 m feature is tentatively assigned an age of 11 000 years B.P. on the basis of correlation with the sea-level curve of Gibb (in press).

5. *Holocene wedge*

The youngest seismic unit is a prominent, acoustically uniform sediment body that achieves a maximum thickness of 34 m in a localised depocentre at the southern entrance to Molyneux Bay (Fig. 5B). Isopachs reveal an abrupt thinning across the shelf with sediments pinching out just 5 km either side of the depocentre. By comparison, pinch-out, northeastwards along the shelf, does not occur until the Taieri Bight, some 60 km distant.

Identification of the landward limit of the wedge is restricted by the positions of the seismic tracks, all of which begin at least 0.5 km from shore. Off the Clutha River, the wedge thins gradually shorewards and is most likely continuous with the littoral zone for there is no indication of rock barriers in the bathymetric profiles or on hydrographic charts (New Zealand Hydrographic Branch 1967). In contrast, to the northeast, it is commonly confined to landward and/or to seaward by submarine rock exposures, as off the Tokomairiro River (Fig. 3B). The wedge between Nugget Point and Brighton occupies 7.1×10^9 m^3; this figure is derived through application of the "trapezoidal rule" to the cross-sectional areas of 14 seismic sections sited across the inner–middle shelf (see Bannister & Raymond 1972; Carter in press).

For much of its extent, the Clutha wedge is acoustically transparent apart from a few weak and discontinuous internal reflectors. The most persistent of these, here designated reflector R, is usually found uppermost in the wedge, some 10–12 m beneath the wedge surface within Molyneux Bay (Fig. 3A). This reflector's landward limit is not evident but extrapolation shorewards suggests it merges with the underlying transgressive surface at around −27 m, a depth which is sometimes marked by a well-defined rock platform (Fig. 4A). To seaward, R is broken by cut and fill structures (Fig. 3A), but, despite this localised erosion, it has a progradational downlap relationship with the transgressive surface.

The outline and consistent depth of occurrence of reflector R seems to define a wedge which implies the Clutha wedge is a composite feature with two main components: (1) an inner wedge, defined by reflector R and designated W3 after the terminology of Carter et al. (1986) and (2) the overlying wedge, W1 (Fig. 3A, B).

The precise age of W3 is uncertain. That it probably pinches out a c. −27 m, sometimes at a rock platform (Fig. 4A), suggests W3 originated against a shoreline situated near this depth. Thus, a tentative correlation is made with a 9600–8800 year old shoreline at −24 m, documented from the Christchurch area, 400 km to the northeast of Molyneux Bay (Suggate 1968; Gibb in press). Wedge W1 is regarded as modern, having accumulated since sea level stabilised about its modern position 6500 years ago. This age is based on the stratigraphic position of W1, its proximity to the modern shoreline (Carter et al. 1985), its lithologic characteristics (Andrews 1973), and sediment budget considerations which show the wedge is actively growing (Carter in press).

MODERN WEDGE (W1) SEDIMENT

The typical surficial sediment of wedge W1 is a light olive grey, well sorted to moderately well sorted, fine to very fine sand (mean size 2.1ϕ–3.5ϕ; standard deviation 0.4ϕ–0.9ϕ). This sediment fines seawards across the wedge, except near its seaward limit where mixing with coarse biogenic debris raises the mean grain size (Fig. 2). Sand becomes finer northeastwards along the shelf, at least in the central reaches of the wedge. A small (< 10%) mud component is present near the Clutha River and at the seaward limit of the wedge off Nugget Point (Carter & Ridgway 1974; Andrews 1979).

The modern sand of the inner shelf has a distinctive mineralogy of quartz, feldspar, and mica accompanied by a heavy mineral suite rich in garnet and epidote-clinozoisite. This reflects a Haast Schist provenance area drained principally by the Clutha River (Williams 1979). In contrast, coastal sand south of Nugget Point contains hornblende and hypersthene which are typical of a plutonic provenance in the Foveaux Strait–Western Province (Martin 1961; Bardsley 1977). As these sediments are swept northeastwards into Molyneux Bay, they are overwhelmed by Clutha sediment (Bardsley 1977). However, on the middle shelf, Foveaux Strait–Western Province sand has travelled along the outer wedge as far as the Taieri River in quantities equal to the Clutha-derived component (Williams 1979).

W1 sand has a low biogenic content. Calcium carbonate concentrations typically range between 10 and 25%, rising to 42% at the seaward edge where mixing with biogenic-rich relict/palimpsest sediments occurs.

EVOLUTION OF THE WEDGE

Carter et al. (1982, 1985, 1986) demonstrated that the postglacial transgression over the eastern South Island shelf was not uniform but took place in a series of steps each separated by a stable shoreline against which a sediment wedge often formed. The seismic data lead us to contend that the Clutha wedge evolved in at least two distinct stages, each stage corresponding to a major stillstand of sea level during the Holocene phase of the transgression (Fig. 6).

About 9600 years ago, sea level stabilised at c. −27 to −24 m and occupied this depth range for the next 800 years (e.g., Gibb in press). During this stillstand, Molyneux Bay was partially emergent, comprising a gently seaward dipping coastal plain on top of Pleistocene sediments. Outside the bay, the seabed was basically a basement rock platform, broken by ridges and pinnacles, and incised by several wave-cut benches formed during previous stillstands (Fig. 6A).

Molyneux Bay favoured wedge accumulation because (1) sediment was available from the nearby Clutha River and the Southland shelf (Carter in press) and (2) Nugget Point provided protection from southerly storm-driven currents (e.g., Carter & Herzer 1979). Therefore, a sediment wedge, W3, formed across the mouth of the 9600–8800 year old Clutha estuary (Fig. 6B). Seaward progradation of the wedge was unhindered within the embayment. However, beyond the confines of Molyneux Bay, progradation was temporarily checked, as indicated by the eroded strata seaward of Nugget Point (e.g., Fig. 3A). There, sediments would be fully exposed to the along-shelf current regime and transported northeastwards into the Taieri Bight where further sand was contributed by the Taieri River.

Accumulation of W3 sediment diminished with resumption of the shoreline transgression, c. 8800 years B.P., when drowning of the ancestral Clutha River mouth presumably would have forced it into an aggradational phase. This stage of the transgression was rapid with only a brief pause at c. −9 m (7500 years B.P.) before reaching its present position.

With the attainment of modern sea level, Molyneux Bay was completely inundated and became the depositional site for the fine to very fine sandy load from the Clutha River (Fig. 6C). Other sediment was contributed from the coast and shelf, south of Nugget Point (Bardsley 1977; Williams 1979).

Effects of the modern hydraulic regime

As the modern wedge developed, it came under the influence of an active current and wave regime which has been responsible for wedge morphology and transporting sediments to the northeast (Carter et al. 1985). The terrace-like surface of the wedge, for instance, is widest in the sheltered waters of Molyneux Bay, whereas, in more exposed reaches to the northeast, the width rapidly diminishes and the terrace form is lost.

The 30 m depth of the terrace edge appears to be related to the limit at which wave-induced sediment movement most frequently occurs. Wave data from the middle shelf off Oamaru shows the mean wave has a significant period $T^{1/3}$ = 7.4 s and significant height $H^{1/3}$ = 1.8 m (Pickrill & Mitchell 1979). Following linear Airy wave theory (Komar & Miller 1973), the near-bottom orbital speed generated by this wave at the terrace edge is 16.5 cm/s. This speed compares well with a threshold speed of 15 cm/s estimated for 0.125 mm diameter grains (Komar & Miller 1973) typical of Clutha sand.

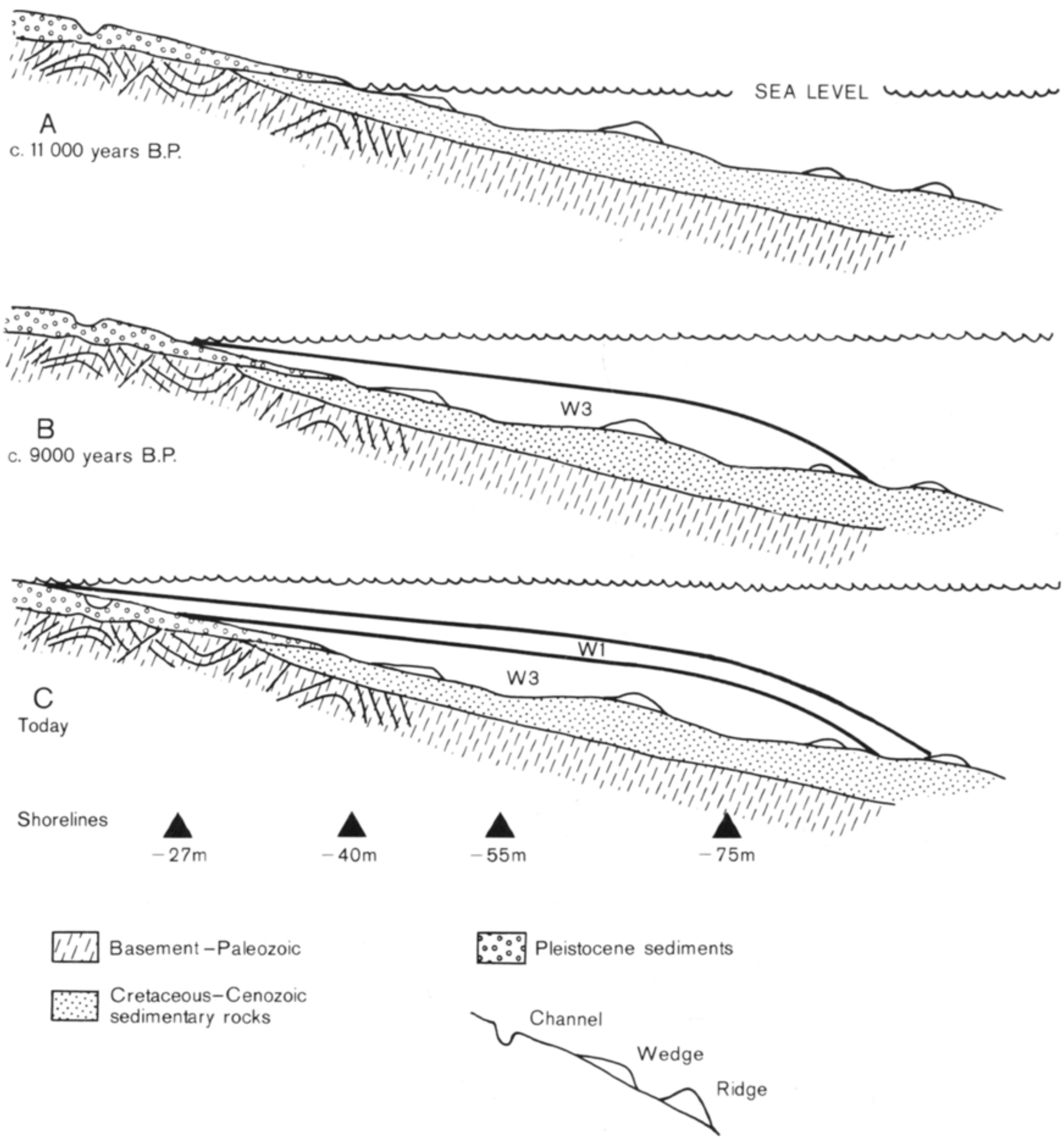

Fig. 6 Three key stages of the evolving Holocene wedge dated from available sea-level data of Herzer (1981), Carter et al. (1985) and Gibb (in press).

The combined influences of the mean flow (Southland Current), tides, and southerly storm induced currents have produced a net northeasterly transport of W1 sand — a trend that is substantiated by textural and petrologic distribution patterns (Andrews 1973; Williams 1979; Carter et al. 1985). These currents have the combined power to transport fine sand on the shelf in at least −75 m depth (Carter & Herzer 1979).

Sediment transport directions are also influenced by shelf morphology. Ridges and other elevations in the basement have guided sediment along the shelf. Off the Tokomairiro River, ridges have separated the main body of the wedge from the near-

shore zone, thus denying it sand from the adjacent coast. However, where the local coastal supply is significant, as immediately off the Taieri River, basement irregularities are inundated and the wedge appears to be continuous to the littoral zone.

To date, the northeast front of the sand wedge and its peripheral apron have travelled 60 km along the middle shelf from its main source (the Clutha River) at an average rate of 9 km/10^3 years. The rate of advance has probably varied in response to changes in sediment supply, shelf hydraulic regime, or climate. Shelf currents appear to be halting the advance of the wedge in the north Taieri Bight, where the re-entrant shape of the wedge front is probably controlled by a localised southwestward current, formed by deflection of the regional northeastward flow against Otago Peninsula (Carter et al. 1985).

In contrast to sand on the middle shelf, W1 sand has travelled along the innermost shelf and littoral zone relatively unimpeded. As a result, Clutha sand now extends at least 190 km northeast of the river (Bardsley 1977; Gibb 1979). The minimum average rate of littoral advance over the past 6500 years is 29 km/10^3 years. Again, the actual rate probably varied with time; for example, Nicholson (1979) suggested the littoral supply of Clutha sand increased markedly over the last 200–500 years when beaches in Blueskin Bay began to form.

Variations in rates of wedge growth

If the Clutha wedge developed according to the model outlined in Fig. 6, then there appears to be major changes in rates of wedge accumulation during the Holocene.

In those profiles best showing what we interpret as wedge W3 (e.g., Fig. 3A), the wedge constitutes about 40% of the cross-sectional area. If this percentage is valid for the Clutha wedge in its entirety, then the volume of W3 is c. 40% of 7.1×10^9 m^3 (i.e., c. 2.8×10^9 m^3). As W1 and W3 are regarded as depositing against shorelines that were stable for 6500 years and 800 years respectively (e.g., Gibb in press), a significant difference in accumulation rates becomes apparent (Table 1).

The difference is most likely a reflection of climatic changes such as the marked warming in the Southland–Otago area c. 9400 years ago (McGlone & Bathgate 1983). Warming initially would have increased sediment input from the Clutha River through increased glacial runoff in the river's upper catchment within the alpine reaches of the South Island. However, further glacial retreat created the large lakes of Hawea, Wanaka, and Wakatipu. Thus, three major sediment traps formed downstream of an extensive catchment with a high sediment yield (Adams 1980). The Clutha River was, therefore, denied large volumes of sediment, judging by the thicknesses of presumed postglacial deposits in these and other South Island lakes (e.g., +150 m Lake Wakatipu, +200 m Lake Pukaki, R. A. Pickrill, New Zealand Oceanographic Institute, pers. comm. 1986).

Table 1 Estimated accumulation rates for wedges W3 and W1. In calculating these values it has been assumed that the wedges formed mainly during the period of stillstand. However, a wedge may also incorporate sediment deposited during the transgression preceding the stillstand. Core and seismic evidence (Carter et al. 1985; this study) reveal the transgressive sediment sheet is typically thin (c. 1–2 m) and, consequently, its presence in the major wedges discussed in the text would not significantly alter the proposed accumulation rates.

Wedge	Volume (m^3)	Shoreline stillstand (years)	Accumulation rate (m^3/year)
W3	2.8×10^9	800	3.5×10^6
W2		not detected	
W1	4.3×10^9	6500	0.7×10^6

This entrapment mechanism would be a valid explanation for the reduction in accumulation rates if the timing of lake deglaciation and trap formation occurred during or after W3 time. Unfortunately, conclusive age data are lacking for the Clutha region (e.g., McKellar 1960) but the southern lakes of the South Island were glaciated up to at least 12 000 years B.P. (Suggate et al. 1978). This age approaches the lower 9600 year age of W3 suggesting the lake-entrapment argument may be viable.

Supply to W3 may also have been increased by the availability of loess which appears to have been undergoing its last major period of accumulation c. 9400 years B.P. (Bruce 1973; Ives 1973). A further pulse of sediment may have come from the Southland shelf. The 12 000–9500 year phase of the transgression breached Foveaux Strait which previously was a broad coastal plain (Cullen 1967). This breach instigated strong tidal flows which, together with wind-driven currents and the ancestral Southland Current, would have eroded the coastal plain to produce an influx of sediment to the Southland shelf and eventually to Molyneux Bay.

CONCLUSIONS

1. The Holocene wedge on the inner–middle shelf off South Otago appears to be a composite feature of a lower wedge, W3 (volume c. 2.8×10^9 m^3) overlain by 10–12 m of modern terrigenous sand,

W1 (volume c. 4.3 × 10^9 m^3). W1 and W3 sediments were supplied mainly by the Clutha River, with lesser contributions from the Southland shelf and Taieri River.

2. Wedge W3 initially developed in Molyneux Bay, probably against a shoreline at c. −24 to −27 m, c. 9600–8800 years ago. A combination of sheltered water and abundant sediment supply caused the wedge to prograde seaward over a variable seabed consisting of near-featureless coastal plain sediments in the southern bay and rugged rock basement to the northeast. However, progradation was probably blunted at the bay mouth by an active current regime which served to transport sand northeastwards. Such transport took place over the rock basement whose shore-parallel ridges guided dispersal and also locally isolated wedge sediment from the adjacent shore.

3. When sea level stabilised 6500 years B.P., W1 fine sand began to accumulate over the older wedge at a slower rate than for W3. Dispersal was across and along the shelf, the latter being 60 km of transport to the north Taieri Bight, where further transport is inhibited by an inferred local current flowing counter to the regional northeastward flow. By contrast, littoral transport has moved sand at least 190 km from the Clutha River.

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