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Late Quaternary Stratigraphy and Sedimentation of the Canterbury Continental Shelf, New Zealand

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R. H. HERZER

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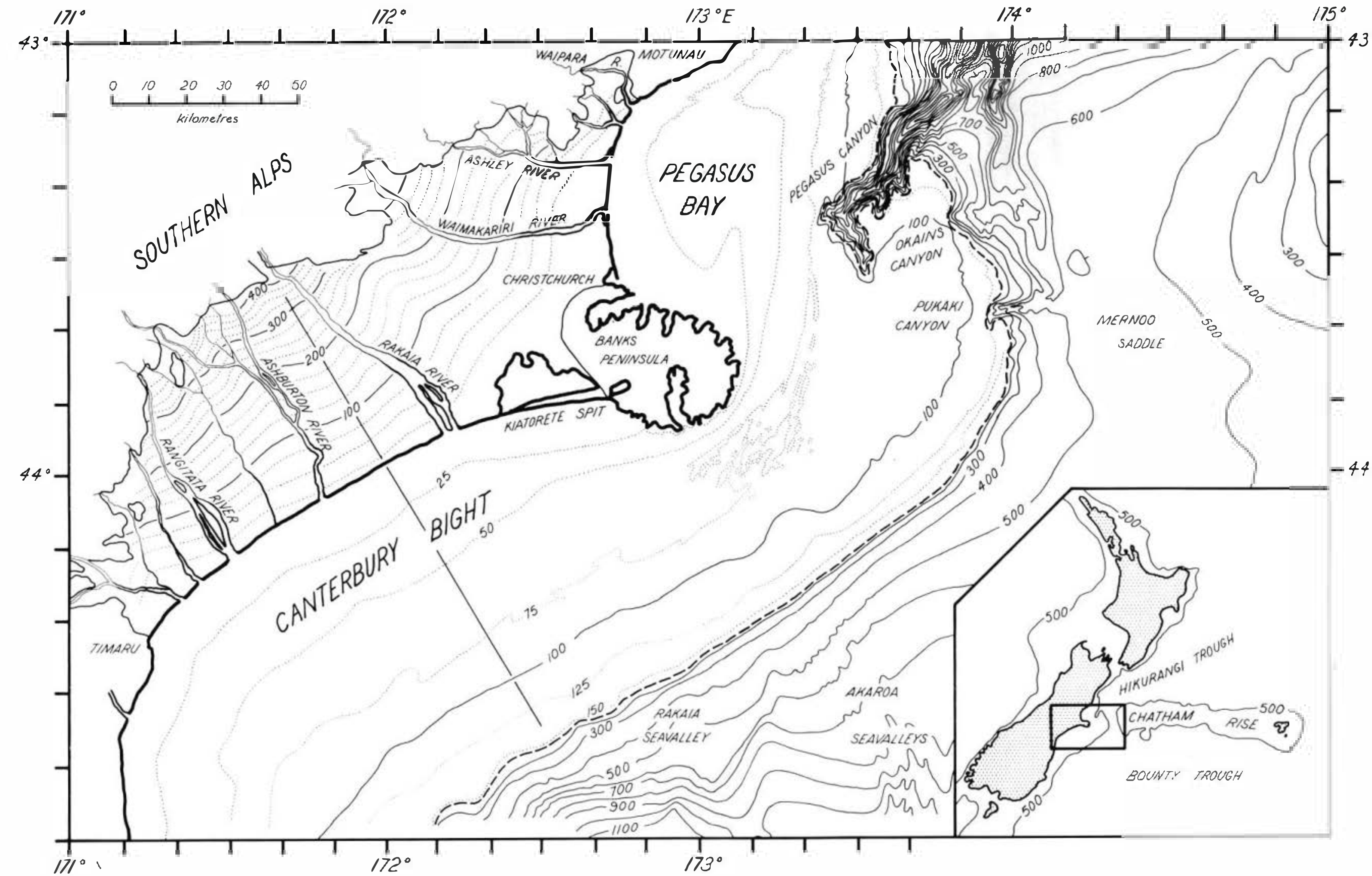

FIG. 1. Bathymetry of the continental shelf and slope off Canterbury, and simplified physiography of the adjacent land area. The shelf edge is represented by a dashed line. The location of the profile in Fig. 17 is shown. Isobaths in metres.

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ABSTRACT

The Late Quaternary stratigraphy and sedimentary processes are interpreted for an area of continental shelf on the eastern side of the South Island, New Zealand. The area extends from latitude 43° 00'S to latitude 44° 50'S and includes Pegasus Bay, the shelf around Banks Peninsula, and Canterbury Bight.

Two formations are recognised and defined in the Late Quaternary stratigraphy: the Canterbury Bight Formation and, locally overlying it, the Pegasus Bay Formation. They are identified by extensive unconformities (visible in high resolution seismic profiles), by geomorphology, by grain-size modes, and by macrofauna. The Canterbury Bight Formation underlies the entire continental shelf in the study area, where it is subdivided into lower and upper members. The lower member, deposited during the high sea level of the Last Interglacial and the falling sea level of the Last Glacial, consists of prograded very fine marine sand and mud. It is now exposed only near the shelf edge and on the continental slope. The upper member was deposited during the Last Glacial as a littoral/fluvial blanket on the regressive marine lower member, and was then reworked during the subsequent deglacial transgression. It is composed of gravel and medium and fine sand. This member is exposed on the inner shelf of central Canterbury Bight, where vestigial fluvial geomorphology is preserved, and on the middle shelf around Banks Peninsula where both relict littoral geomorphology and relict and modern sublittoral geomorphology are recognised. The Pegasus Bay Formation forms the present shelf surface off prograding portions of the coast and on those parts of the shelf that are not swept by strong currents. It is composed of very fine marine sand and mud, and represents the net accumulation of new sediment supplied to the shelf since the Holocene return to relatively stable high sea level.

Ridge-and-swale topography occurs on two scales on the shelf. Very large, coast-parallel ridges and troughs are interpreted from detailed bathymetry, stratigraphy, sediments and macrofauna to be the remains of Pleistocene spit/lagoon complexes. With the aid of radiocarbon dates, the remains of four

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well developed shorelines between 28,000 yr and 15,000 yr old are recognised. Smaller ridges and troughs are interpreted as submarine features formed by strong currents. Those ridges that are in a zone of constricted and accelerated currents near Banks Peninsula appear to be active, while those well removed from the peninsular constriction are partly buried by muddy sediments, and date from times of lower sea level.

Studies of sediment texture and provenance show that net sediment movement on the shelf and along shore during both Late Pleistocene and modern times has been northwards. The submarine canyons of the north-eastern shelf were probably the main Pleistocene sediment sinks. The present day flow of sediments is mainly into Pegasus Bay.

Sedimentation on the continental shelf has reached a state of equilibrium with the modern hydraulic regime. Relict sediments of the deglacial transgressive sand/gravel sheet are being reworked in zones of high energy (principally in the region of constricted flow around Banks Peninsula) into lag gravels, sand ridges, sand ribbons and sand waves. Modern-input sand (distinguished by its grain size mode) is restricted mainly to an active belt near shore as a result of current action, but locally this sand has replaced palimpsest sand on the middle shelf. The modern mud facies, being confined by zones of higher energy, has reached its maximum areal extent; its greatest thickness is in Pegasus Bay.

Keywords: geology, Late Quaternary, stratigraphy, sedimentation, Canterbury continental shelf, New Zealand.

INTRODUCTION

The eastern continental margin of the South Island of New Zealand comprises a rather narrow continental shelf, flanked seaward by a system of large submarine plateaus and troughs which intersect the landmass at high angles. The continental shelf is almost linear and is exposed to the open ocean for its whole length.

The portion of the eastern continental shelf dealt with in this memoir lies off central Canterbury between 43° 00'S and 44° 50'S (Fig. 1). The eastern shelf reaches its greatest width in this area, which includes Pegasus Bay, the shelf around Banks Peninsula, and Canterbury Bight. It descends very gently to a shelf break at a depth of 130–180 m, the shelf break being approximately 90 km off shore. The shelf lies off a 40 km wide Pleistocene fluvio-glacial outwash plain, the Canterbury Plains, behind which rises a high mountain front, the Southern Alps. An extinct volcanic complex, Banks Peninsula, rising to over 500 m, divides the shelf into Pegasus Bay to the north and Canterbury Bight to the south. East of the continental shelf, the Chatham Rise, with a crestal depth of less than 500 m and shallowing locally to as little as 32 m on Mernoo Bank, extends seaward for more than 800 km. North and south of the rise, the sea is over 2000 m deep. Separating the rise from the continental shelf is Mernoo Saddle with a depth of 550 m.

Rivers entering the sea along the east coast of the South Island drain a hinterland composed mainly of Mesozoic greywacke and argillite in the north, and chlorite zone, quartzo-feldspathic schist in the south (Fig. 2). Small intermontane areas of soft Cretaceo-Tertiary clastics and limestones are present and basic and intermediate volcanics occur locally.

The currents affecting the area have been discussed in detail by Carter & Herzer (1979) and are briefly reviewed here. The various components are tidal currents, the Southland Current, swell, storm waves, wind-drift currents, barotropic currents, and possibly internal waves. During calm weather the north-east-going Southland Current, the semi-diurnal tidal currents, and the dominant southerly oceanic swell can periodically collectively exceed the threshold velocity for fine sand entrainment at a typical inner-shelf depth of 30 m. The frequency of entrainment increases with decreasing depth such that near shore, sand movement is continual. In deeper water, the currents are too weak to move sand except on the shelf off Banks Peninsula where the flow is accelerated by the topographic constriction. During stormy weather, swell, wind waves and wind drift may move sand almost continuously in inner-shelf depths, and less frequently at a typical middle-shelf depth of 75 m. On the outer shelf, such shallow storm currents are largely replaced by barotropic and baroclinic flows and possibly internal waves which, when reinforced by tidal currents and the Southland Current, may be strong enough to move sand on the bottom.

The net direction of mass transport of water on the shelf is north-eastwards (Fig. 3) because, although the north-east-going flood and south-west-going ebb tidal currents are of equal strength, the other principal currents move mainly in a north-eastward direction, viz., the Southland Current is a permanent north-east-going oceanic current; the dominant longshore current is north-eastwards in response to deep-sea swell from the south; and the strongest wind-induced currents flow generally northwards in response to intense and frequent storm winds from the southerly quarter. The southerly winds also generate an on-shore (westerly) component of flow over the inner shelf and a slight off-shore (easterly) component further seawards.

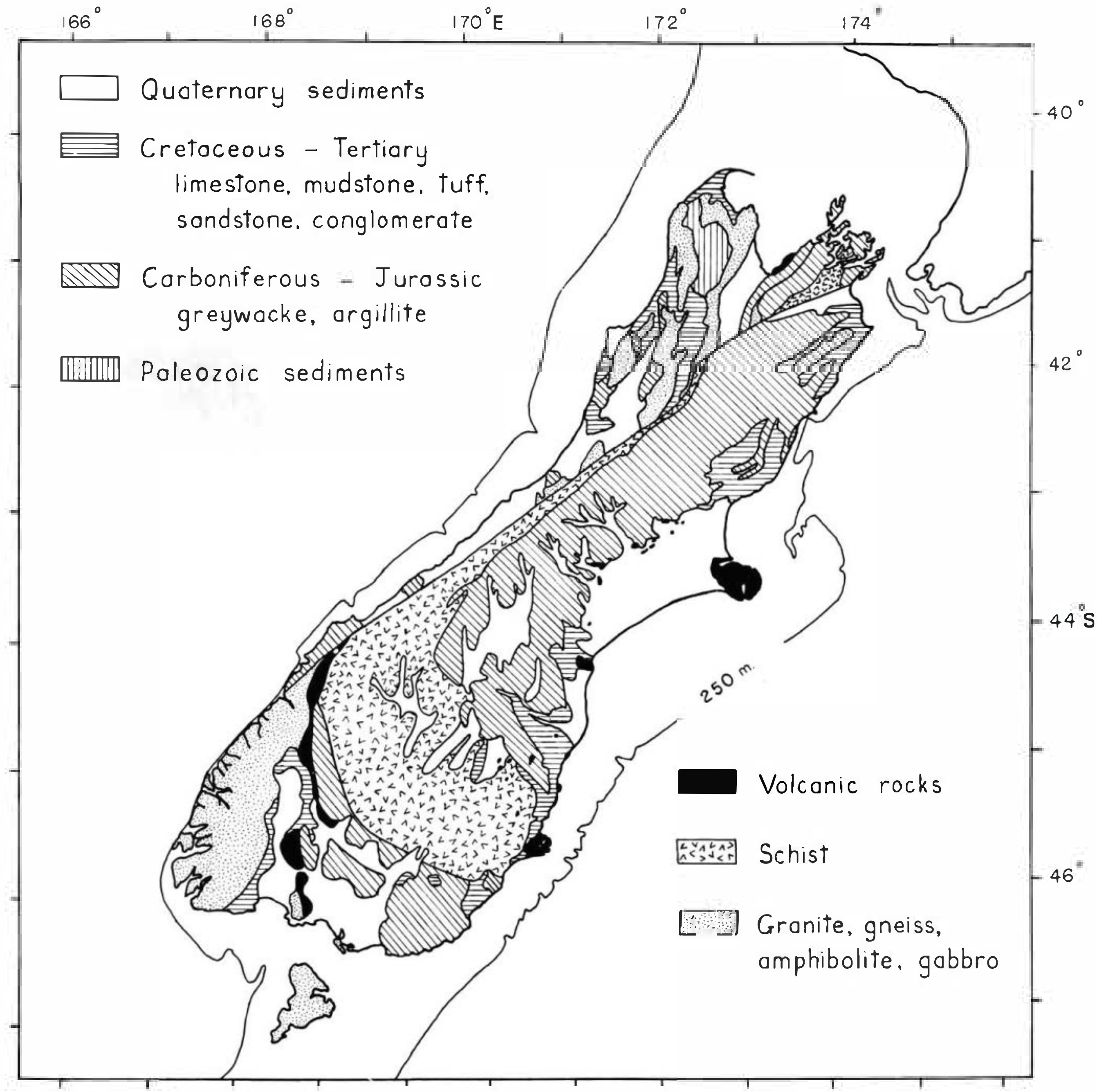

FIG. 2. Simplified geology of the South Island. Modified from NZ Geological Survey 1972: Geological map of New Zealand.

BATHYMETRY

METHODS

The first step in the geologic investigation of any piece of sea bottom is (or should be) bathymetric mapping. All available bathymetric data were accordingly compiled (Fig. 4) and contoured (Figs 1, 5, 6).

In areas where detailed surveys have been done, such as Pegasus Bay and west of Banks Peninsula, the detailed bathymetry was contoured from the collector sheets of the Hydrographic Branch, Royal New Zealand Navy. An obvious and fairly systematic

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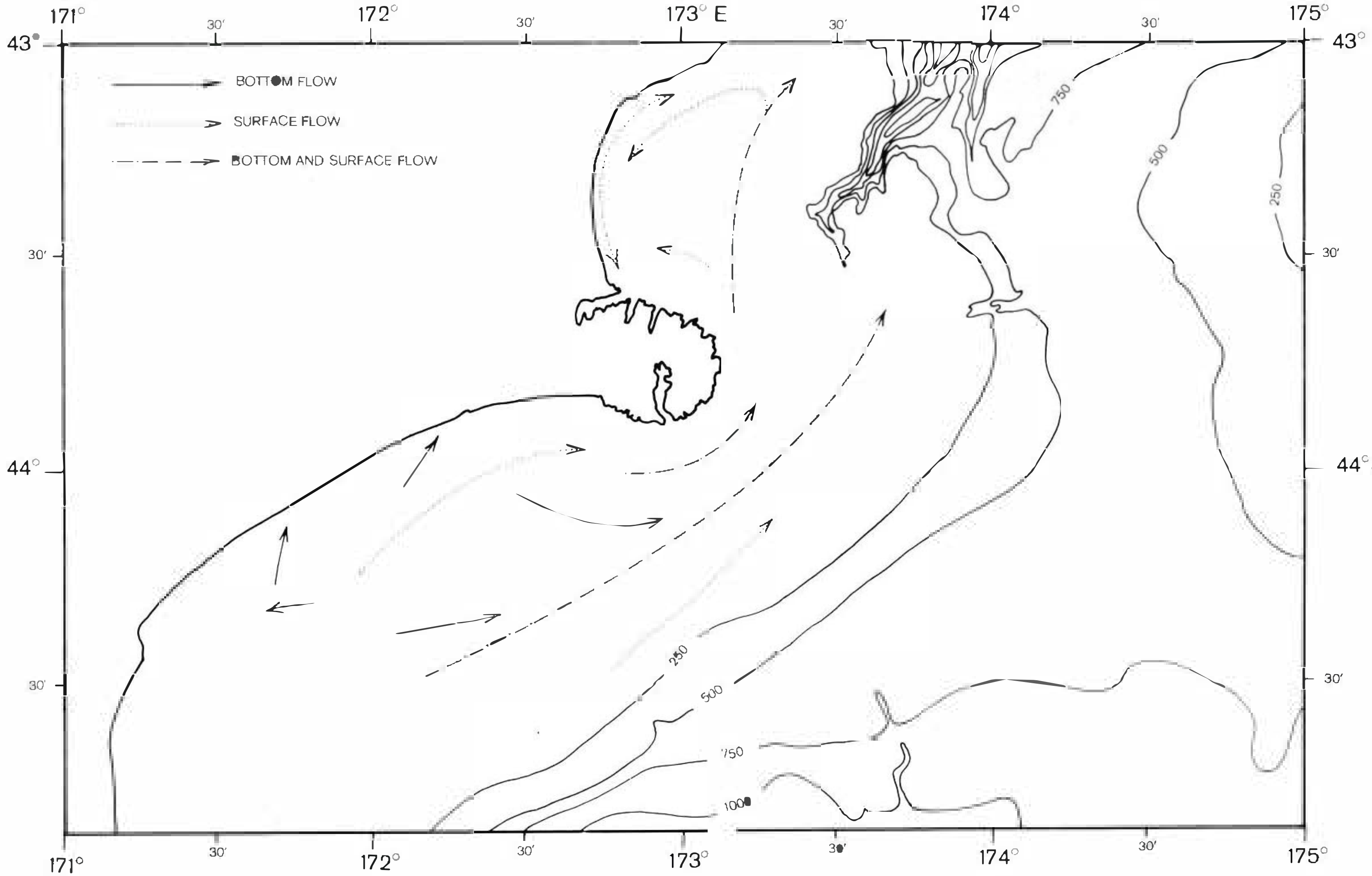

FIG. 3. Direction of net water flow on the Canterbury shelf, based on drift card, sea-bed drifter and *Landsat* II information. Modified from Carter and Herzer (1979) and Cochrane *et al*. (1976).

surveying error along some of the sounding lines on the collector sheets created a spurious bathymetric trend that had to be filtered. The spurious nature of this trend was confirmed by echo-sounding profiles made by the author. The echo-sounding lines of the hydrographic survey, closely spaced, parallel with each other, were run in a north-south direction in some areas and an east-west direction in others. When the depth values were contoured, isobaths crossing the lines at a high angle formed a sharp zig-zag pattern that was always parallel with the trend of the survey lines and clearly superimposed on the actual gross bathymetric trend. The error was one of depth and not one of position, since a large displacement of contour lines (generally in the order of 1–2 km) occurred where the slope is gentle – on the continental shelf – and no displacement occurred where the slope is steep – in submarine canyons or on the continental slope. The error was approximately ± 0.5 m, and when allowed for, it became possible to contour with a 2 m vertical interval.

South of Banks Peninsula no detailed survey had been made. In order to deduce the geomorphology, every available echo-sounding profile (Fig. 4) was examined, and features such as slight changes of slope, areas of smooth or undulating sea bed, highs, depressions, terrace-like features, etc., were plotted. It was found that most features could be correlated from profile to profile and tied in with those shown by the detailed bathymetry to the north.

GEOMORPHIC ZONES OF THE CONTINENTAL SHELF

The morphology of the shelf surface shown in Figs 5 and 7 is described below. Its probable mode of origin is discussed later. It consists of a series of zones which are generally parallel to the strike of the shelf.

Zone A

Zone A includes almost all of Pegasus Bay plus a narrow band extending south around Banks Peninsula and into Canterbury Bight as far south as the Rakaia River. It generally stands above the rest of the continental shelf, its seaward limit being easily recognised along much of its length by a relatively steeply sloping (2.0-6.0 m km^{-1}), convex suface terminating abruptly against the more level shelf to the east (0.6–1.0 m km^{-1}). Within Pegasus Bay, the zone comprises a broad, very shallow trough with slopes of 0.2-0.8 m km^{-1}, open to the north, and bounded on the east by a long, low bank, projecting north from the north-eastern extremity of Banks Peninsula. Around Banks Peninsula it consists of a narrow, sloping apron 7 km wide. It widens in Canterbury Bight to a shallow platform 20 km wide. The surface of Zone A on echograms is smooth and even.

Zone B

In the north-western corner of Pegasus Bay, where the coastline is rocky, a rough surface of low relief (Zone B) occupies a coastal belt about 10 km wide.

Zone C

Zone C lies adjacent to the coast south of the Rakaia River, where the coastline is cliffed. The zone does not stand high above the rest of the shelf as does Zone A. Its slope is slightly steeper than the more level shelf to seaward, but merges imperceptibly with it at a depth of approximately 60 m. Bathymetric contours within the zone (Fig. 1) describe two adjacent, broadly convex, arcuate surfaces with a slope of 1.2–1.4 m km^{-1} extending 35 km off shore from the two great alluvial fan surfaces of the southern Canterbury Plains. It shows on echograms as a smooth surface with local wave-like features superimposed. The wave-like features are asymmetrical, with steep slopes facing north to north-west; they have a peak-to-trough amplitude of approximately 1 m and a wave length of approximately 2 km.

Zone D

Zone D occupies a mid-shelf position and stretches from about 44° 30′S northwards to Pegasus Canyon. Zone D generally has a much gentler overall slope (0.6–1.0 m km^{-1}) than the landward zones (with the exception of Zone A in Pegasus Bay) and it terminates seaward at a line where the slope of the shelf again increases (2.5–5.0 m km^{-1}).

The surface of this zone is uneven and echograms display a gently rolling profile that is characteristic of ridge-and-swale topography. Echograms and detailed bathymetry show that the ridge-and-swale topography is made up of two distinct types of ridges: small ridges with heights of 1–14 m crest-to-trough, widths of 1–2 km across the base, and crest lengths of 10 km or more (Fig. 6); and very large ridges of generally similar height, but with widths of 9–13 km across the base and crest lengths of 30–50 km (Fig. 5). The large ridges are termed here "first-order ridges", and the small ridges, "second-order ridges". Second-order ridges are locally superimposed upon first-order ones.

In Canterbury Bight, second-order ridges are concentrated in two long, roughly parallel bands, incompletely separated by patches of smooth bathymetry (Fig. 7). The bands run parallel to the general trend of the bathymetric contours, the landward band occurring along the south-eastern margin of the near-shore Zone A, and the seaward one occurring at the line where the bathymetry again steepens seawards at about 80–90 m depth.

Where the continental shelf is narrow south-east of the peninsula, Zone D occupies most of the width of the shelf. Within it, neither a two-fold areal distribution nor first-order ridges are evident and the zone is dominated from east to west without interruption by high second-order ridges with crest-to-trough amplitudes up to 14 m.

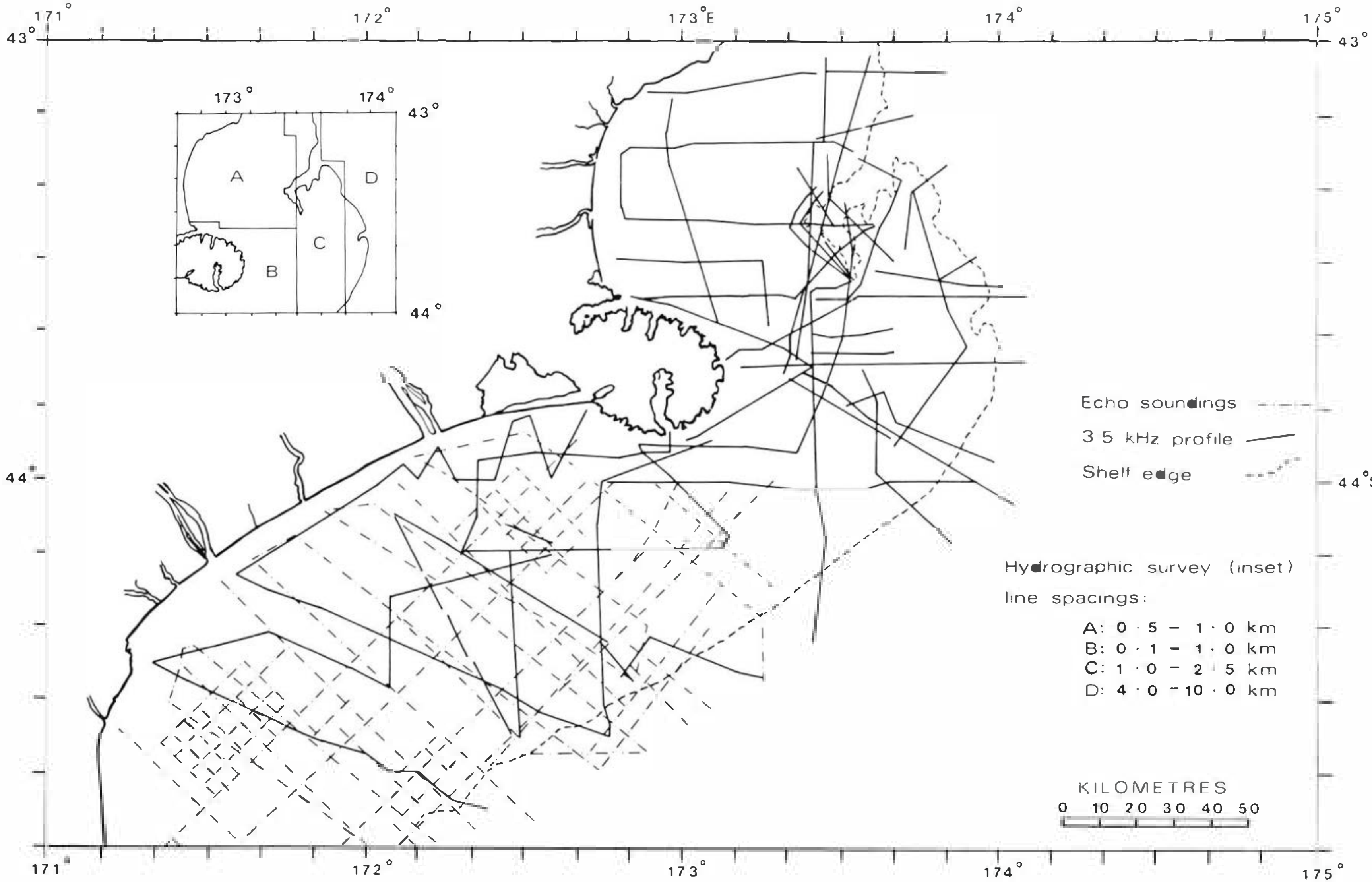

FIG. 4. Echo sounding coverage of the continental shelf off Canterbury. Reliability diagram (inset) shows area covered in detail by hydrographic surveys.

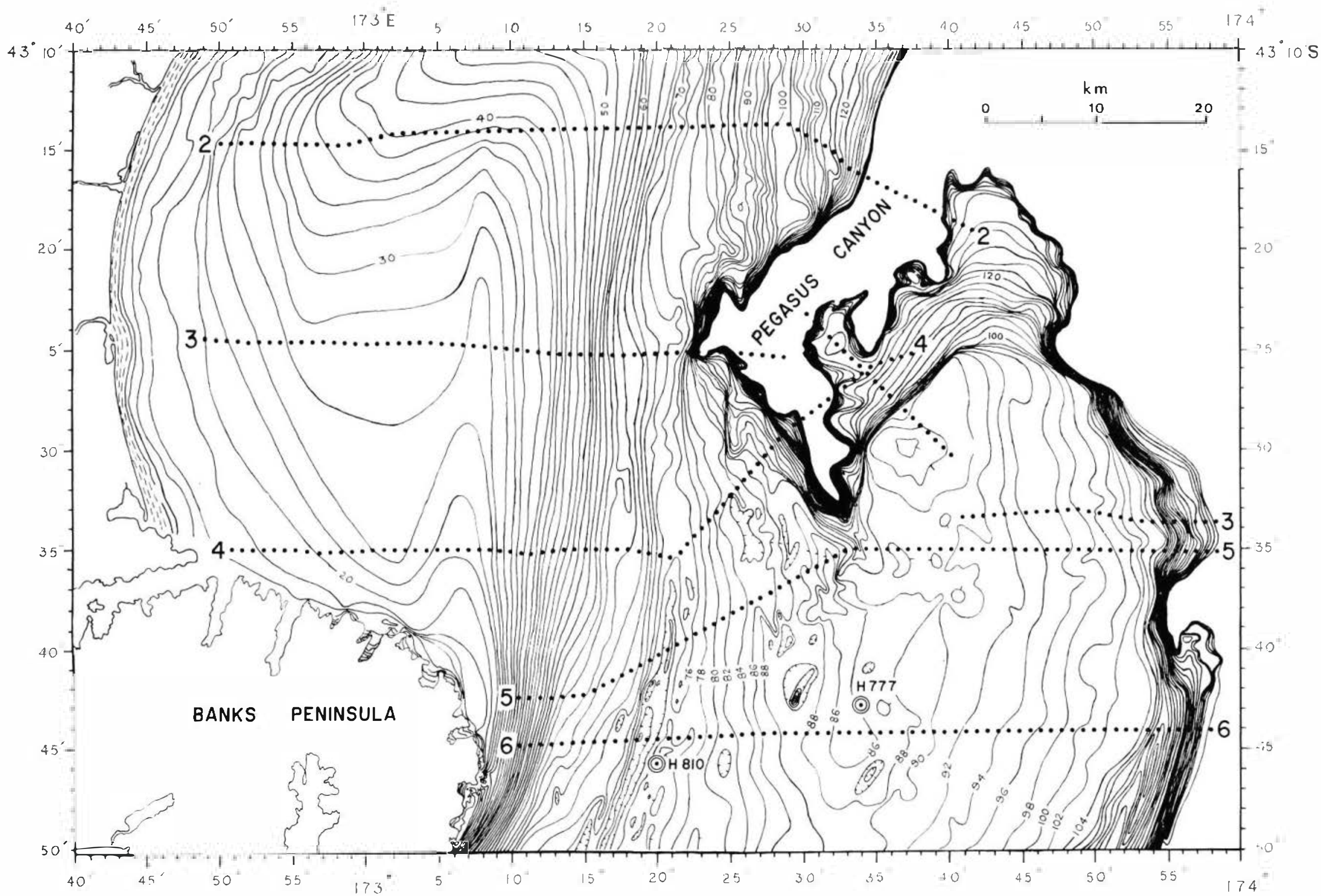

FIG. 5. Detailed bathymetry of Pegasus Bay and the shelf off Banks Peninsula. *See* Fig. 4 for reliability diagram. Dotted lines are locations of 3.5 kHz profiles appearing in Figs 19–21. Isobaths in metres.

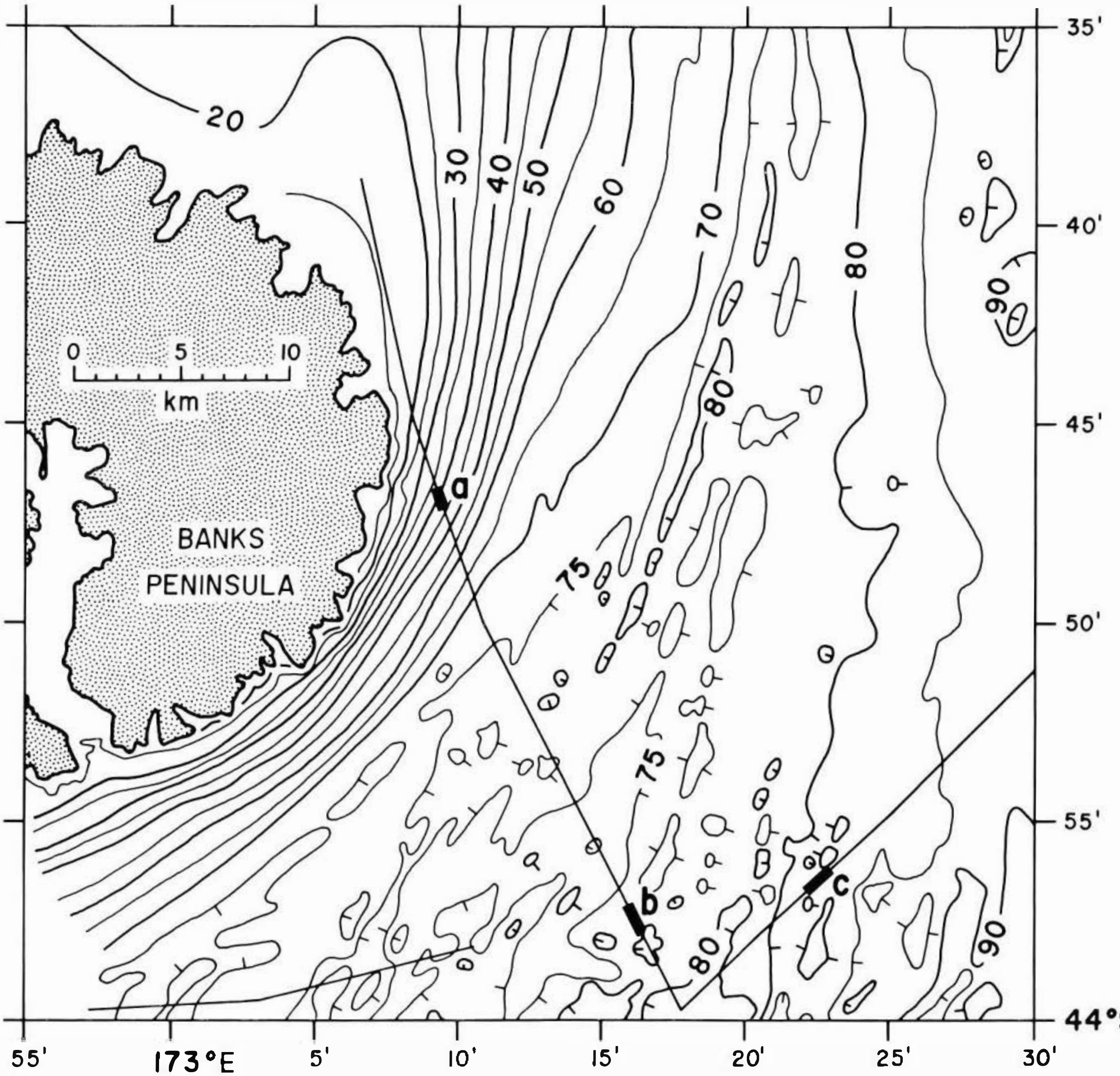

FIG. 6. Bathymetry of a portion of the second-order ridge-and-swale topography off Banks Peninsula. Locations of side-scan sonar lines are shown. Isobaths in metres.

North of latitude 43° 55'S the second-order ridges become abruptly sparser, and within 10 km, virtually disappear. Two parallel first-order ridges, each with a trough on its landward side, continue north towards Pegasus Canyon.

The eastern ridge of the first-order pair lies just inside the 90 m isobath and is broad and indistinct (Figs 5, 7). Its crest is 84–86 m below sea level and its associated landward trough is, on average, 90 m below sea level. There are several relatively small, closed basins in the trough, the deepest being 100 m below sea level. The ridge branches at about 43° 40'S, the eastern branch appearing as a very subdued high east of the head of Pegasus Canyon and the western branch forming a narrower and more pronounced ridge which trends into the western side of the canyon head.

The western ridge of the first-order pair has a depth of 74–76 m below sea level along its crest and its landward trough has a fairly consistent depth of 80 m below sea level. Ridge and trough both terminate at 43° 35'S where they merge with steeper bathymetry off eastern Pegasus Bay.

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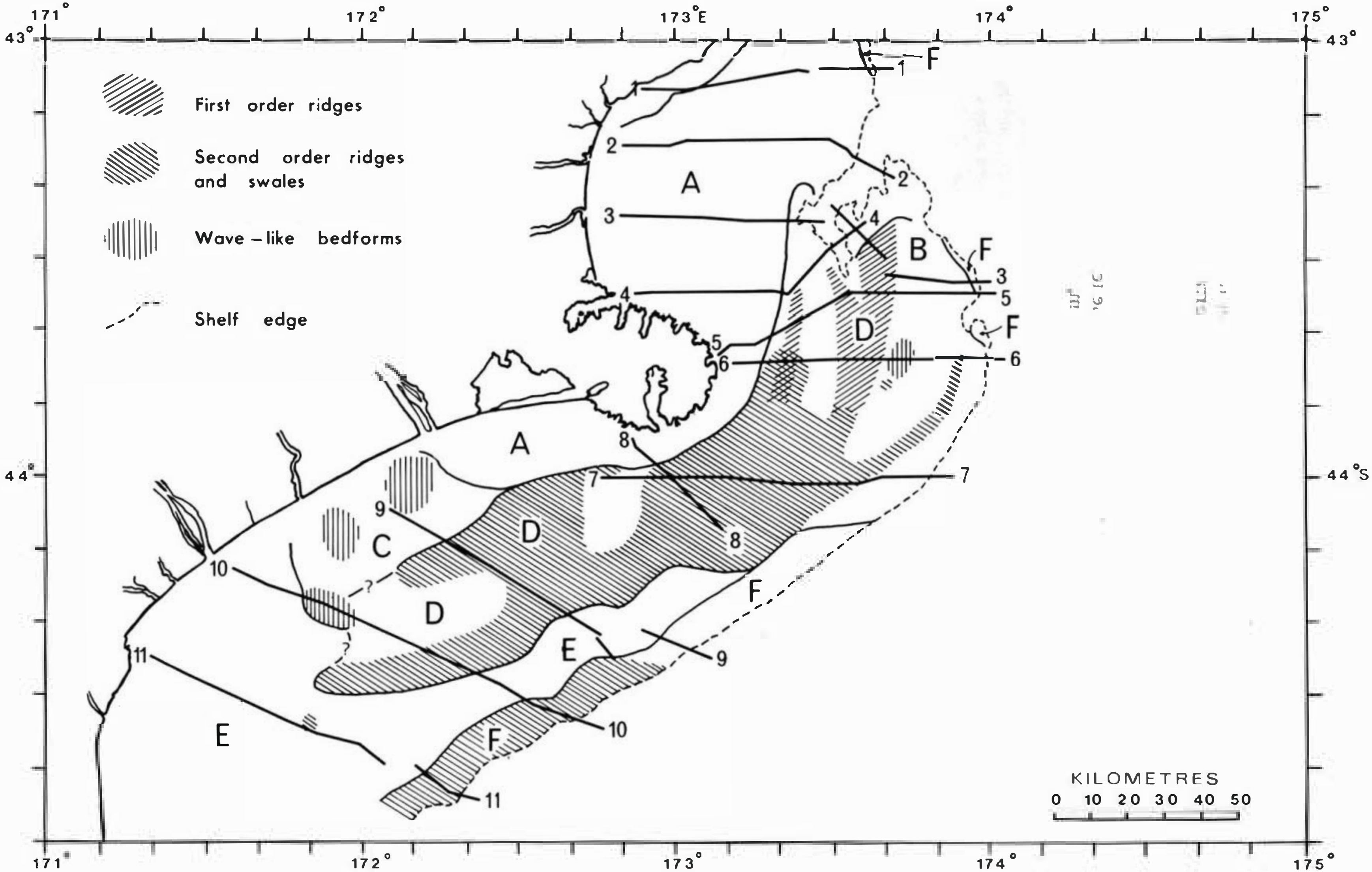

FIG. 7. Geomorphic zones of the Canterbury continental shelf, and locations of 3.5 kHz profiles appearing in Figs 19–23.

At the northern end of these first-order ridge systems, shallow troughs leading into the canyon are prominent in the bathymetry. East of the eastern first-order ridge the shelf simply slopes gently seawards for 25 km as a broad platform with an uneven surface, steepening near the shelf edge.

Zone E

In Canterbury Bight the ridge-and-swale zone passes seaward and south-westward into a zone of smooth, even bathymetry. The seaward change is marked by an increase in slope; the south-westward change simply by a gradual disappearance of the ridges. This region of smooth bathymetry is designated Zone E. Its seaward portion forms a relatively steeply sloping (2.5 m km^{-1}) belt about 11 km wide running parallel to the shelf trend and tapering out north-eastwards at about latitude 44° 13′S. To the south-west it widens landward to include most of the shelf, but undergoes subtle changes of slope which reflect the slopes of the distinctive zones to the north-east. From the coast in this area down to a depth of 40 m, 20 km off shore, the slope is approximately 2.0 m km^{-1}, slightly convex, and reminiscent of Zones A and C in central and northern Canterbury Bight. There are no wave-like features on the echograms, however. The slope becomes more gentle seaward, approximately 1.3 m km^{-1} south of adjacent Zone D, but is free of ridges. It then steepens again 40 km off shore at 70 m depth to approximately 2.5 m km^{-1}.

Zone F

Zone F is a terrace 4–9 km wide that skirts much of the shelf edge of the study area. North of 44° 25′S, the surface of the terrace is smooth and even; to the south it has a gentle second-order ridge-and-swale topography.

The depth of this terrace is variable. The depth of the lower limit of the terrace (the shelf break) ranges from about 130–180 m, and that of the nick point at the upper edge of the terrace from about 110–150 m. The greatest depths are found along the distal portions of the shelf east of Banks Peninsula, and the shallowest on the narrow shelf at the northern edge of the study area and in the upper reaches of Pegasus Canyon. Intermediate depths prevail off southern Canterbury Bight.

The terrace is slightly anomalous in the region of Pegasus Canyon. It is 9 km wide along the south-east side of the main trunk of the canyon but is absent on the canyon's west and north sides. The terrace is also absent on the narrow portion of the shelf adjacent to Banks Peninsula.

SEDIMENTS

SAMPLING

A total of 332 surface samples and 23 cores were studied (Figs 8, 9). The cores and 224 of the surface samples were obtained during three cruises by the author on r.v. *Tangaroa* in 1973 and 1975. The remaining samples came from the NZOI collection. The bulk of the surface samples were obtained with a modified Hayward orange-peel grab and a small number with a Deitz-Lafond grab. Cores were obtained with a 6 m Kullenberg-type piston corer.

The shipboard processing of samples was as follows. A representative subsample (to be used later for textural analysis) was taken from each grab sample. For sandy and muddy sediments, about 400 ml were taken; for very gravelly sediments, several litres were taken. The remainder of the grab sample was washed through a screen and the pebbles and shells retained were bagged. Living specimens were preserved in alcohol. Cores were stored vertically aboard ship in their plastic liners. On shore they were cut to storage size and stored horizontally prior to analysis.

Surface sampling was mostly on a grid pattern with a spacing of about 10 km. Coring was restricted to sites deemed important.

ANALYTICAL METHODS

Each of the surface sediment samples obtained on the three *Tangaroa* cruises plus any relevant samples in the NZOI collection was homogenised, split, and wet sieved with a 4Φ sieve. The relative amounts of lithic gravel, shell gravel, and sand (including carbonate) were determined by dry weight. The amount of mud was determined by the pipette method of Folk (1968). The colour of the dry sand fraction was noted (Geological Society of America 1963). Complete pipette analyses of the silt/clay fraction were performed for a small number of samples only. A complete sieve analysis using the following mesh sizes (in Φ units) was carried out on approximately half of the samples (Fig. 8): −1, −0.5, 0, 0.5, 1.0, 1.25, 1.50, 1.75, 2.00, 2.25, 2.50, 2.75, 3.00, 3.25, 3.50, 3.75 and 4.00 Φ. This data is presented in the author's thesis (Herzer 1977, Appendices 2, 3) or may be obtained by writing to the author.

This sieve distribution was adopted after trial runs using a complete 0.25 Φ interval set on a number of representative samples had revealed the dominant grain-size populations. Material smaller than −1.0 Φ was brushed through the large sieve with a paint brush

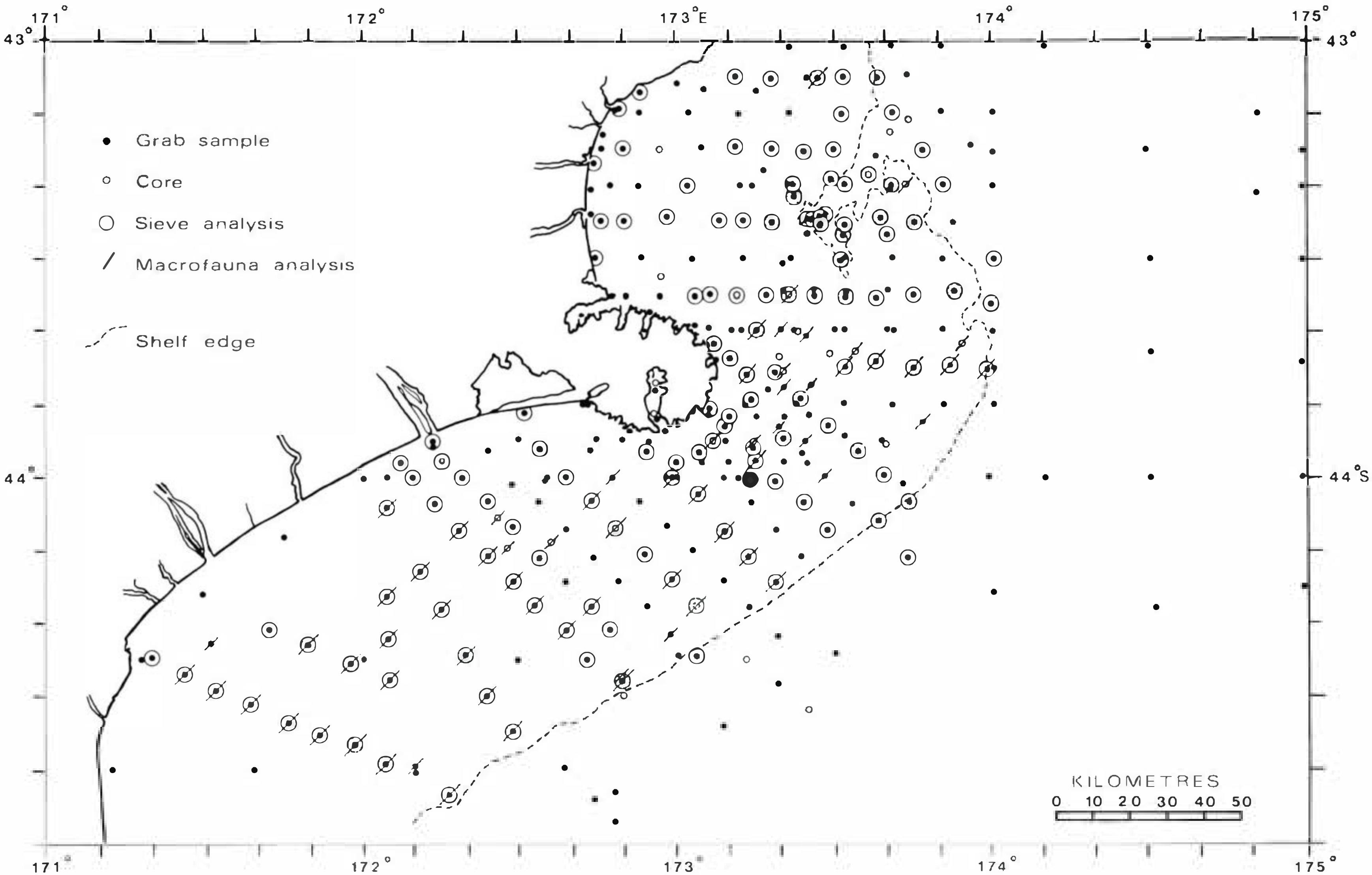

FIG. 8. Locations of sample stations.

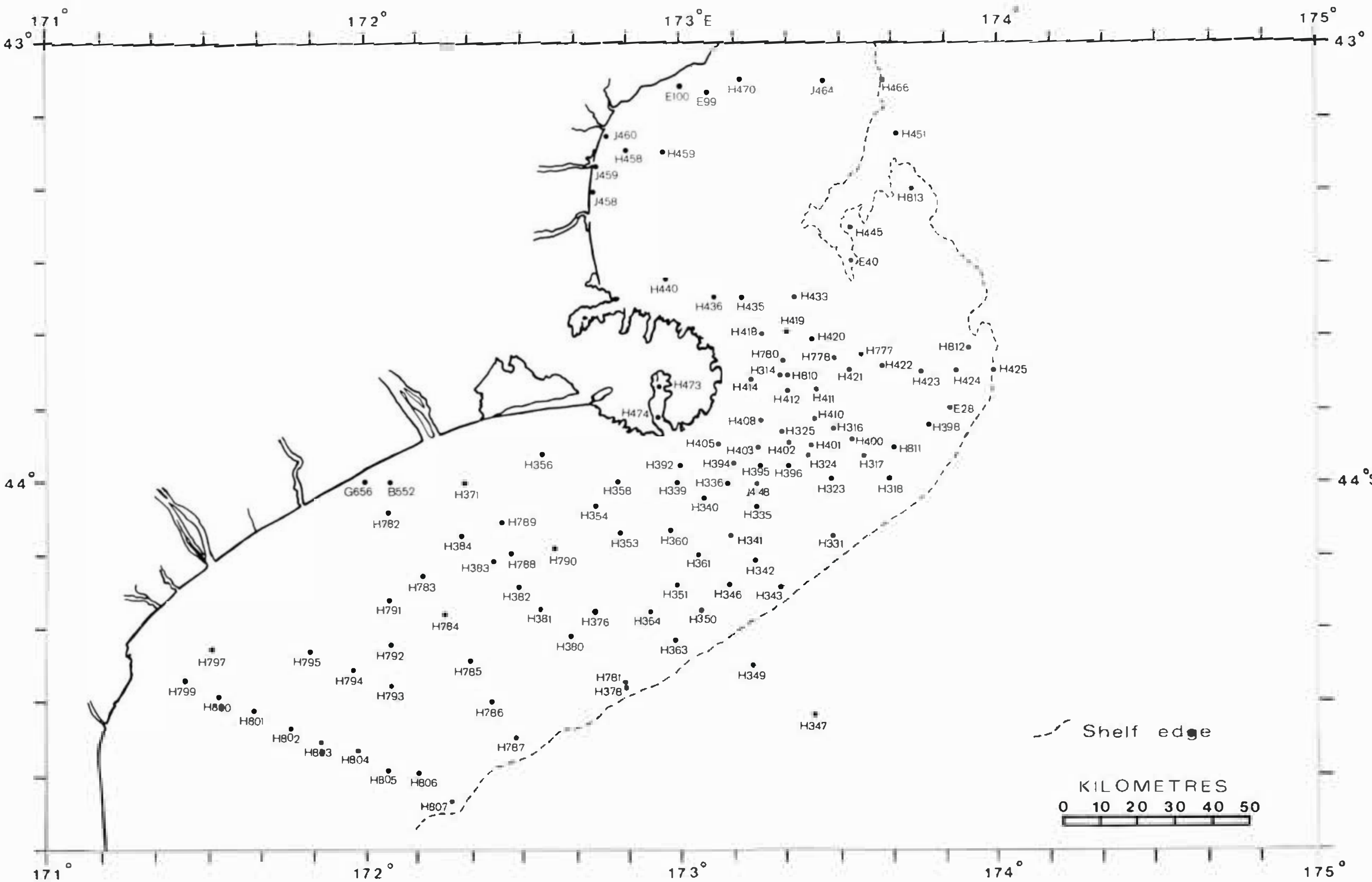

FIG. 9. Locations of sample stations referred to by number in the text.

to avoid abrasion of the commonly shelly and delicate gravel sized material. The 16 sand sizes (−0.5 to +4.0 Φ) were sieved for 15 minutes on an Endecotts shaker which could accommodate eight sieves at a time. Each sieve fraction was examined under a binocular microscope and the relative proportions of clastic shell sand, foraminifera and terrigenous sand were estimated. The carbonate sand content was low and did not significantly affect the fraction weights.

The pebbles that had been washed from the remainder of each grab sample after subsampling on board ship were examined for a provenance study. The relative abundances of visually determined rock types in each of two size classes (−3 to −2, and > −3 Φ) were recorded (Tables 1, 2). Where there was sufficient gravel in a sample, 100 pebbles were identified; but in many samples, gravel was rare and smaller numbers had to be used. Besides the gravel, certain sand fractions obtained from the 0.25 Φ sieve analyses were examined petrographically for the provenance study (Table 3).

The shells washed from the remainder of each total grab sample at 54 stations along selected sample lines (Fig. 8) were identified and the relative abundance of

TABLE 1: Lithology of pebbles in the −3ø to −2ø size range

	Quartz	*Schist*	*Greywacke (+ Argillite)*	*Other Rocks*	*Grains Counted*
B552*	6	–	94	–	16
E28	68	–	32	–	22
E40	25	–	70	5	20
E99*	–	–	93	7	15
E100	–	–	100	–	11
H314	95	–	5	–	42
H316	65	–	33	2	46
H317	89	–	11	–	82
H318	82	–	18	–	44
H323*	70	1	25	4	100
H324*	83	1	15	1	100
H325	94	5	1	–	100
H335	91	1	6	2	100
H336	92	1	3	4	100
H339	23	–	68	9	22
H340*	83	2	13	2	100
H341	100	–	–	–	54
H346*	70	1	24	5	100
H351	93	1	3	4	119
H360	95	–	1	4	100
H361	81	2	16	1	168
H364	80	–	20	–	69
H376*	80	–	17	3	100
H378	81	–	14	5	57
H380	63	–	37	–	46
H382	16	–	79	5	19
H383	22	1	72	5	100
H384*	13	2	78	7	100
H394	89	–	3	8	35
H395*	93	–	5	2	105
H396*	94	–	6	–	100
H398*	88	–	11	1	100
H400	69	1	21	9	104
H401*	66	1	32	1	100
H402	92	–	5	3	100
H403	89	1	3	7	100
H408	91	–	8	1	100
H410	78	1	19	2	115
H412	90	2	4	4	100
H418	78	–	18	4	27
H421	80	1	15	4	100
H423	78	–	19	3	100
H424*	74	–	21	4	99
H425	80	2	14	5	63
H470	3	–	91	6	100
H782*	2	–	95	3	100
H785	75	–	22	3	32
H787	78	–	22	–	9
J448	93	–	4	3	71
J458	–	–	100	–	8
J459*	–	–	100	–	5
J460	2	1	83	14	79

*The sample number appears in the analysis of coarser gravel in Table 2.

TABLE 2: Lithology of pebbles larger than -3ϕ

	Quartz	Schist	Greywacke (+ Argillite)	Other Rocks	Grains Counted
B552	–	–	100	–	5
E99	–	–	100	–	3
G656	2	–	95	3	20
H323	26	–	66	8	144
H324	50	–	50	–	16
H340	69	2	23	6	51
H346	41	9	47	3	34
H376	63	1	33	3	202
H384	2	–	96	1	78
H395	64	2	29.5	4.5	44
H396	67	–	33	–	18
H398	56	2.5	39	2.5	36
H401	65	–	32	3	60
H424	51	3	46	–	61
H470	3	–	94	3	30
H782	–	–	98	2	100
J459	–	–	100	–	15

each species noted (Table 4). The lack of faunal analyses from Pegasus Bay is a reflection of the extreme paucity of shells in that area and not of bias in sample selection.

Cores were split, logged and photographed (Herzer 1977, Appendix 4), those obtained on the first cruise (H347–H474) being X-radiographed prior to splitting; shell horizons were sampled, the fauna identified (Table 5), and selected material submitted for radiocarbon dating (Table 6). In most cases, only a single species was submitted for dating, and then only if it was a dominant species in the core. Where two species had to be used in order to make up the required sample weight, they were from closely related environments. Wherever possible shells of species restricted to shallow water were selected. The material submitted for dating was apparently free of borings and of biological or chemical encrustations.

In order to obtain an on-shore reference collection for provenance study, 38 river, beach, and cliff grab samples were taken along the coast from the Waipara River (43° 09′S) south to Dunedin (45° 55′S). River bed samples were collected where possible from midstream bars and beach samples from the wet foreshore below the most recent high water mark. The lithology of the gravels was determined visually. The modes in the sand fraction of selected samples were determined by standard sieving techniques with a 0.25 Φ sieve spacing.

The textural size classes used are those of Wentworth (1922) and Folk (1968).

SELECTION OF SIGNIFICANT TEXTURAL PARAMETERS

When interpreting the environment of continental shelf sediments from their textures, one has to remember that the sampling is by necessity crude relative to the complexity of the environment being studied.

During the last 18,000 years the sea has transgressed inland across the continental shelves of the world, and the whole of the shelf environment has changed. The normally fining-seaward sequence of clastic sediments is restricted to the inner shelf, while the sediments of the outer shelf comprise coarse detritus abandoned during the deglacial transgression (*see* e.g., Pilkey & Frankenberg 1964, Curray 1965, Emery 1968). These so-called "relict" sediments on the outer shelf, although not replenished by modern sediment input, remain mobile where energy conditions are sufficiently high, and sediment waves, sand ribbons, linear ridges, etc., may form from these relict sediments and migrate across lag pavements or exposed semi-indurated surfaces (*see* e.g., Stewart & Jordan 1964, Belderson *et al.* 1971, Stubblefield *et al.* 1975, and Swift *et al.* 1973). Conversely, where energy conditions are low, relict gravels may be thinly mantled with modern mud. Low or negligible rates of sedimentation on the outer shelf contribute to high concentrations of shell material which have accumulated on the surface over thousands of years. The surface of the continental shelf is therefore a surface having sediments that reflect different environments. For a particular sample the sediment texture may reflect both present conditions and past conditions, the two being very different.

A grab sample is an indiscriminate point sample, the top 10 cm or so of sea bed being collected by the sampler without regard to microstratigraphy. Moreover, in an area where sediment composition may vary considerably over a space of metres, the spacing of samples will significantly affect results. Closely spaced samples or selectively located ones (on the basis of side-scan sonar imagery or direct observation for instance),

TABLE 3: Petrographic analysis of the sand modes

Grains Counted	Indeterminate Rock Fragments	Igneous Rock Fragments	Metamorphic Rock Fragments	Sedimentary Rock Fragments	Indeterminate Minerals	Other Minerals	Glauconite	Muscovite	Biotite	Chlorite	Plagioclase	K-feldspar	Quartz	Mode	Sample No.
195	4.1	0	13.8	13.3	0	0	0	0	0	0.5	3.6	7.6	57.5	IV	**H331**
194	4.6	0.5	5.2	16.0	1.0	0.5	1.0	0.5	0	0.5	7.2	8.5	55.5	IV	**H343**
192	1.6	0.5	12.0	15.1	1.1	0	0	0	0	0	5.2	6.5	59.2	III	**H351**
199	8.5	0.5	7.5	23.1	1	0	0	0.5	0.5	0	1.5	10.4	47.4	IV	**H356**
196	4.6	0.5	12.2	41.8	0	0	0	1	0	0.5	0.5	9.6	30.2	III	**H371**
99	5.1	1	6.1	33.3	1	0	1	0	0	0	0	2.7	39.7	III	**H395**
99	9.1	0	4	26.3	1	0	0	0	0	0	0	8.2	61.4	III	**H423**
199	6.5	0	12.1	16.6	1	0.5	0	0.5	0	0.5	1.5	9.8	52.0	IV	**H436**
197	2.5	0.5	4.6	13.2	2	0.5	0	0	0.5	0	3	6.9	65.7	IV	**H445**
197	2	0.5	3	17.8	0	0	4.1	0	0.5	0	3	6.8	62.2	IV	**H458**
192	0	1	7.3	20.4	0.5	0.5	0	0.5	0	0.5	3.6	8.5	57.7	IV	**H466**
163	2.5	2.5	6.1	32.5	0	0	0.6	0	0	0	2.5	12.8	40.6	III	**H470**
152	5.3	2.6	9.2	46.7	0	0.7	0	0	0	0	2.0	8.7	24.9	III	**H782**
118	3.4	0	8.4	12.7	0.8	1.7	0.8	0.8	0	0.8	0	3.8	66.6	IV	**H784**
196	2.6	0.5	11.2	20.9	0.5	0.5	0	1.5	0.5	1.0	1.5	7.6	51.6	IV	**H793**

Explanation of Terms:
Quartz – includes single crystal, finely and coarsely polycrystalline, strained and unstrained grains; grains with sericite and chlorite inclusions; and some grains with secondary overgrowths
K-feldspar – includes altered and unaltered orthoclase, microcline and some perthite
Plagioclase – altered and unaltered
Other minerals – including zoisite, hornblende, sillimanite, serpentine, rutile
Sedimentary rock fragments – mainly sandstone, argillite, some chert
Metamorphic rock fragments – mainly greenschist facies, pelitic and psammitic (greywacke) derivatives
Igneous rock fragments – includes volcanic and leucocratic plutonic rocks

TABLE 4: Benthic macrofaunal assemblages in selected surface samples
* = abundant, + = common, – = rare

Taxon	Depth range	Occurrences in samples
BIVALVIA		
Anomia sp.		+ + – – + – + – * * * +
Atrina zelandica (Gray, 1835)	0–30	* +
Aulacomya maoriana (Iredale, 1915)	0	
Barbatia novaezealandiae Smith, 1915		
Cardita aoteana (Finlay, 1927)		*
Caryocorbula (Anisocorbula) zelandica (Quoy and Gaimard, 1835)	0+	+ + – + + * + * – + – + + + + +
Chione (Austrovenus) stutchburyi (Gray, 1828)	0–4	– + +
Chlamys (Mimachlamys) incl. {*C. gemmulata gemmulata* (Reeve, 1853), *C. zelandiae* (Gray, 1843)}	10+	+ + + + – + – + + + + + + * – + + + + + + + + + + + + * * * + + + + – – + + + + + – + + * + – – + + + *
Chlamys (Zygochlamys) delicatula (Hutton, 1873)	0–40	– + – +
Cuspidaria sp. incl. {*C. fairchildi* Suter, 1903; *C. trailli* (Hutton, 1873); *C. willetti* Fleming, 1948}		– – + –
Diplodonta (Zemysina) globus (Finlay, 1927)	0–90	* – + – + * + + * + – – + + + + + + – +
Divaricella (Divalucina) huttoniana Vanatta, 1901		+ + + – * – + + + – * * + + – +
Dosinia (Austrodosinia) anus (Philippi, 1848)	0–20	
Dosinia (Dosinia) lambata (Gould, 1850)		+ – + + +
Dosinia (Kereia) grayi (Zittel, 1864)	20–40	+ + * + – + * + * * * * *
Dosinula zelandica (Gray, 1835)		+
Escalima regularis Powell, 1955		
Gari sp. incl. {*G. lineolata* (Gray, 1835), *G. stangeri* (Gray, 1843)}	0–20	* * * + * * + – + + +
Glycymeris (Glycymerula) modesta (Angas, 1879)	0–80	* * * * * + *
Lima colorata colorata Hutton, 1873		+ –
Limatula maoria Finlay, 1927	0–220	– + –
Mesopeplum convexum (Quoy and Gaimard, 1835)	10–200	–
Modiolarca impacta (Hermann, 1782)		+ + –
Modiolus areolatus (Gould, 1850)		
Myadora biconvexa Powell, 1927		+ + + – *
Myadora novaezelandiae Smith, 1880		+ + – – + – + – + + + + +
Myadora striata (Quoy and Gaimard, 1835)	0–20	+ + – * + + + +
Myadora sp. incl. {*M. antipoda* Smith, 1880; *M. boltoni* Smith, 1880; *M. subrostrata* Smith, 1880}	8+	– + + – + – * + + +
Mytilus edulis aoteanus Powell, 1958		
Nemo sp. incl. {*N. australis australis* (Quoy and Gaimard, 1835), *N. rugata* Dell, 1956}	10–275	– + –
Nemocardium (Pratulum) pulchellum (Gray, 1843)	10–200	+ – + – – + + + + + + + + + * – + + + * + + + + + * – * + + * * + + + + + – – + * * * * + +
Notocallista (Striacallista) multistriata (Sowerby, 1851)	20–75	* + + + * – + + + + – + * + * + + + * + + – + + + * * + + – * * + – + + + + + * – *
Nuculidae incl. {*Ennucula strangei* (A. Adams, 1856), *Nucula strangeiformis* Dell, 1956}	0+	+ + – + – + + + + + + * – + + + * + – + + – + – + + – + * – +
Ostrea sp.	0–30	+ + * + – +
Paphies (Mesodesma) subtriangulatum (Wood, 1828)	0–3	+ + * * – + *
Paphies (Paphies) australe australe (Gmelin, 1791)	0–3	* + + * +
Paphies (Tavia) ventricosum (Gray, 1843)		
Pecten novaezelandiae novaezelandiae (Reeve, 1852)		
Pleuromeris zelandica (Deshayes, 1854)	0–200	+ + * – * * * * * * * * * + + * * + * – – + + – * – + + * + + + + – * * * * * * * * * – + + * * * * * * +
Proleda lanceolata (Hutton, 1885)		+ – – – + + + + +
Pullastra largillierti (Philippi, 1847)	0–20	+ + +
Saccella bellula (A. Adams, 1856)	8–300	+ + – + * * + * * * * * – + + * * * – – – + + + * + * – – – * * * + – * * * * + – – * * * * * + + –
Scalpomactra scalpellum (Reeve, 1854)	0–90	– – – – – + + + – + + + * * + * * – – * + – – – + – – – + – +
Spisula aequilateralis (Deshayes, 1854)	0–20	
Tawera spissa (Deshayes, 1835)		* + + – – – – – – – + – * * – + + * * + – + + * * + + – – – + * + – – + + – * – + – – – +
Tellinella charlottae (Smith, 1885)		– – – + – – + – + – – + + – – * + + + + – – – * – + – + + + + +
Tellinella huttoni huttoni (Smith, 1885)		– * *
Thracia vegrandis (Marshall and Meredith, 1919)		+ * + – *
Thracia vitrea (Hutton, 1873)		–
Thracia sp.		
Venericardia purpurata (Deshayes, 1854)	0–30	* + * + + + * + – + – * * + – + – – – * + + –
Zenatia (Zenatia) acinaces (Quoy and Gaimard, 1835)	0–110	– * – + + – – +
Bivalvia indet.		– + – +
GASTROPODA		
Amalda (Gracilispira) novaezelandiae novaezelandiae (Sowerby, 1859)	0–200	– – – – – + –
Antisolarium egenum (Gould, 1849)	4–70	+ +
Argalista fluctuata (Hutton, 1883)		
Argalista nana Finlay, 1930		–
Austrofusus (Austrofusus) chathamensis Finlay, 1928		– – –
Austrofusus (Austrofusus) glans (Roeding, 1798)		+ – – – + + – + + + – + + + + + + + – + + + +
Austrofusus sp.		+ +
Buccinulidae/Cominellidae		– – – – +
Cylichna thetidis Hedley, 1903		–
Emarginula striatula (Quoy and Gaimard, 1834)	0+	

Table 4

Species	Approximate depth range (m)	H323	H324	H325	H339	H340	H341	H342	H343	H350	H351	H353	H354	H358	H363	H376	H378	H380	H381	H382	H383	H384	H395	H398	H411	H412	H414	H418	H419	H420	H421	H422	H423	H424	H425	H782	H783	H784	H785	H786	H787	H791	H792	H793	H794	H795	H797	H799	H800	H801	H802	H803	H804	H805	H806	H807	J464
Epitonium sp. incl. *E. philippinarum* (Sowerby, 1844)																																																			—	—	—	—	+		
Glaphyrina sp.																																																									
Leporemax fusus (Quoy and Gaimard, 1843)																																																									
Maoricolpus roseus roseus (Quoy and Gaimard, 1843)	0–70															+											+									+				+			+								+						+
Maoricrypta (Zeacrypta) monoxyla (Lesson, 1830)	0+												+	+													+	—																													
Maoritonella albula (Hutton, 1873)																																																									
Marginellidae incl. { *Marginella (Volvarinella) subfusula* Powell, 1932; *Marginella (Sinuginella) pygmaea* (Sowerby, 1846) }																																			+																						
Maurea sp. incl. *M. foveauxana* (Dell, 1950)																																																									
Micantapex angustatus Powell, 1940																																																									
Micrelenchus huttoni (Smith, 1876)		+	—	+		—	+						+	—																						*																					
Naticidae incl. { *Proxiuber australe* (Hutton, 1878); *Tanea zelandica* (Quoy and Gaimard, 1832); *Uberella vitrea* (Hutton, 1873) }															—	+										+								—	+																	+	—	—	+		
Patellids indet.		+																																																							
Pervicacia tristis (Deshayes, 1859)	0–40																																																								
Phenotoma novaezelandiae (Reeve, 1843)	0–60																																																								
Poriteria kapua Dell, 1956	20–200																																																								
Pyramidellidae incl. *Agatha georgiana* (Hutton, 1885)																																																			*					
Splendrillia aoteana Finlay, 1930																																			*																						
Trochidae incl. { *Coelotrochus tiaratus* (Quoy and Gaimard, 1834); *Thorista viridis* (Gmelin, 1791) }	4–110																																			+																					
Xymene ambiguus (Philippi, 1844)																																																									
Xymene sp.	0–20																																																								
Zeacolpus (Stiracolpus) symmetricus (Hutton, 1873)	4–130	+	—	—		—	+	*	—	+	+				+	+	+	+	+	+				+	+	—											—	+	+	+	+	*	+	*	*		+		+	+	*	*	*	+	*	—	+
Zeatrophon sp.																																				+																					
Zegalerus tenuis (Gray, 1867)	0+												+	+												+	—	+								+	+	+	—									—	+	+	—						
Zethalia zelandica (A. Adams, 1854)	0–20										—	—	+			+			—	—	+	+	+		+							—	+	—										*	+	+											
Gastropoda indet.																					+																																	—	+		
SCAPHOPODA																																																									
Dentalium (Fissidentalium) zelandicum (Sowerby, 1860)																																																									
Dentalium (Antalus) nanum Hutton, 1873	30–200							—	—	+	—	+	—	+	—		+	+	—	—																		—	+	—	+		+						+	+	—	—	—	—	—	—	—
BRACHIOPODA																																																									
Neothyris lenticularis (Deshayes, 1839)		+	+				+	+	+	*					+	+	*	*						*						—	+		*	*	*				—	*	+	•									—	—	+	*	*		
Terebratella sanguinea (Leach, 1814)																							—	+									—	+	+	—																					
OTHER GROUPS																																																									
Arthropoda																																																									
Cirripede fragments												+	+	+	+						+	+			*	—	+	+	+	+	+					+	—	+					+	—	—	+		+		+	+	+					
Crustacean fragments																																																									
Bryozoa: bun-shaped, branching, encrusting		+	*	+			+		+			—	+	—	+	+	+	+	+	—	—	+	—	*	+	*	+	+	+	*	*	*	*	*	+				+	+	+				—	+			+	+	—	—	—	+	+	+	
Echinoid fragments			*									+	—	+							+				*	—	+	+					+	—	+											+	+	—		+	—						
Polychaete tubes							*		+	+	*	+	+	+	+	+	+	+		+	+			*				+				—	+	+	*			+		+	+			*				+	—	+		—	—	—	+	+	
Flabellum rubrum (Quoy and Gaimard, 1833)									+																																																
Ophiuroidea																																																									

Station No.

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TABLE 5: Benthic macrofaunal assemblages in cores
• = abundant, + = common, – = rare

BIVALVIA

Taxon	Depth (m)	Occurrence in cores
Anomia sp.		– +
Aulacomya maoriana	0	+ + +
Bathyarca cybaea Hedley, 1906		
Cardita aoteana		•
Caryocorbula zelandica	0+	
Chione stutchburyi	0–4	• + + +
Chlamys (Mimachlamys) incl. {*C. gemmulata*, *C. zelandiae*}	10+	+ – – – – – + – – – + + •
Chlamys (Zygochlamys) delicatula	0–40	+
Diplodonta globus	0–90	– + +
Divaricella huttoniana		+ – – – – – • •
Dosinia grayi	20–40	+
Dosinia lambata		+ + –
Dosinia (Phacosoma) subrosea (Gray, 1835)	0–20	– + +
Dosinia sp.		–
Escalima regularis		
Gari sp. incl. {*G. lineolata*, *G. stangeri*}	0–20	• + + + + + + – + +
Glycymeris modesta	0–80	+ + – + + + + + + + + + +
Glycymeris (Grandaxinea) laticostata (Quoy & Gaimard, 1833)	0–40	+ +
Lima colorata		
Limatula maoria	0–220	
Mesopeplum convexum	10–200	
Modiolarca impacta		
Myadora biconvexa		– + + +
Myadora novaezelandiae		
Myadora striata	0–20	• – +
Myadora sp. incl. {*M. antipoda*, *M. boltoni*, *M. subrostrata*}	8+	– + + +
Mytilidae		
Mytilus edulis aoteanus		
Neilo sp. incl. {*N. australis*, *N. rugata*}	10–275	–
Nemocardium pulchellum	10–200	+ •
Notocallista multistriata	20–75	+ + – •
Nuculidae incl. {*Ennucula strangei*, *Nucula strangeiformis*}	0+	+ – + + + – –
Ostrea sinuata Lamarck, 1819	0–30	+
Ostrea sp.	0–30	
Panopea sp.	0–20	•
Paphies australe	0–3	+ – + • + + • + +
Paphies subtriangulatum	0–3	– + • • • • •
Paphies sp.		– –
Pecten novaezelandiae		–
Perna canaliculus (Gmelin, 1791)		+ +
Pleuromeris zelandica	0–200	+ + – – – + – + – – – – – + + –
Proleda lanceolata		
Pullastra largillierti		
Saccella bellula	8–300	• + • • – + + – – – – +
Scalpomactra scalpellum	0–90	• • + • • • • + + + +
Spisula aequilateralis	0–20	•
Tawera spissa		– + • + • • • • • • • • • • • • • • – + –
Tellinella charlottae		•
Tellinella huttoni		
Thracia vegrandis		+ – + + + – – +
Thracia vitrea		
Venericardia purpurata	0–30	–
Zenatia acinaces	0–110	+
Bivalvia indet.		+ + – – + –

GASTROPODA

Taxon	Depth (m)	Occurrence in cores
Amalda novaezelandiae	0–200	
Antisolarium egenum	4–70	+ + + + – + – +
Argalista nana		
Austrofusus glans		+ –
Austrofusus sp.		– + + + +
Buccinulum sp.?		
Cominella sp?		–
Daphnella cancellata		
Emarginula striatula	0+	–
Epitonium sp.		

Species	Approximate depth range (m)	H350 90–110	H353 8–32	H403 24–38	H403 38–42	H403 42–49	H405 206–230	H433 30–39	H777 80–122	H777 122–167	H781 80–165	H788 86–98	H788 170–183	H788 213–227	H788 263–316	H789 215–240	H789 258–290	H789 290–308	H790 170–207	H810 60–86	H810 95–142	H812 72–82	H812 166–208	H813 54–71
Eucominia sp.?											+													
Fusitriton sp.?													–	–		+	–	–						
Glaphyrina sp.								–												–	–			–
Maoricolpus roseus	0–70		–				–				+												–	–
Maoricrypta monoxyla	0+		–					–									–	–						
Maoritonella albula																	–	–	–					–
Marginellidae																								–
Maurea sp.											–	–				–		–						
Micrelenchus huttoni						–	–		–	–	–	–	–	–	–		–	–	•			+	+	
Naticidae incl. *Tanea zelandica*		–					–		–	–	+	–	–	+	–	–	–	–	–	–	–	–	–	–
Patellids indet.																			–					
Pervicacia tristis	0–40				–														+	–	–			
Phenotoma novaezelandiae	0–60																–	–	–					
Pyramidellidae			–																					
Splendrillia aoteana																								–
Trochidae	4–110								–	–	–			–				–						
Xymene sp.?	0–20								–	–	–	–	–	–	–	–	–	–	+					
Zeacolpus (Stiracolpus) symmetricus	4–130	+	+	–	+	–	–		–	–	–	+	+	+	+	–	–	–	•	–	–	–	–	•
Zeacolpus (Zeacolpus) vittatus (Hutton, 1873)		–																						
Zegalerus tenuis	0+	–	–								–	–	–	–	–	–	–	–					+	–
Zethalia zelandica	0 20		+	–		–	+	–	+	+		–	–	–	–	–	–	–	•	+	+		–	
Gastropoda indet.								–	–	–	–	–	–	–	–	–	–	–				–		–
SCAPHOPODA																								
Dentalium zelandicum		+	–								–													+
Dentalium nanum	30–200	+	–				–	–								–		–						+
BRACHIOPODA																								
Neothyris lenticularis		–				•																		
Terebratella sanguinea						–																		
OTHER GROUPS																								
Arthropoda																								
Cirripedea			–			–	–	–	+	+	+	+	–	–	–	+	+	+	+	–	–	–	+	–
Crustacea														–					–					
Bryozoa		+	–			–		–			+	+	–	–	–	–	–	–	–	+	+	+	+	+
Echinoidea		–	–		+	–	–	–	–	–		+	+	+	+	–	+	–	+	–	–		–	–
Polychaete tubes		–									–								–	–	–	–		+

Species — Approximate depth range (m) — Core No. and depth in core (cm)

TABLE 6: Radiocarbon ages of shell layers

NZOI Station No.	Latitude	Longitude	Depth of Shells below Sea Level	Depth in Core	Dated Species	Depth Range of Species	Age† (Year B.P.)	NZ No.
H777	43°42.8′S	173°34.0′E	87 m	(a) 0.8 –1.22 m	*Paphies australe* *P. subtriangulatum*	IT 0–3 m*	24500±1000	4763
H777			87 m	(b) 1.22–1.67 m	*Paphies australe* *P. subtriangulatum*	IT 0–3 m*	27900±1550	3890
H788	44°09.6′S	172°27.9′E	59 m	(a) 0.86–0.98 m	*Tawera spissa*	0–120? m	7340± 150	3892
H788			60 m	(b) 1.7 –1.83 m	*Scalpomactra scalpellum*	0– 90 m	8070± 170	3893
H788			60 m	(c) 2.13–2.27 m	*Scalpomactra scalpellum*	0– 90 m	9370± 260	3894
H788			61 m	(d) 2.63–3.16 m	*Scalpomactra scalpellum*	0– 90 m	8560± 220	3895
H789	44°05.4′S	172°25.2′E	56 m	2.52–2.9 m	*Tawera spissa*	0–120? m	6370± 110	3896
H790	44°09.0′S	172°35.8′E	63 m	1.7 –2.07 m	*Zethalia zelandica*	0– 20 m	11750± 250	3897
H810	43°45.7′S	172°19.7′E	76 m	0.95–1.42 m	*Paphies australe* *P. subtriangulatum*	IT 0–3 m*	15100± 200	3898

† Age calculated with respect to old T½ of 5568 yr (Libby 1955).
* IT – Intertidal. Maximum tidal range in New Zealand is <3 m (New Zeland Tide Tables).

if accurately positioned, warrant detailed treatment. Widely spaced grab samples, on the other hand, are only usefully interpreted by simple statistical measures.

The sediments on the Canterbury continental shelf exhibit all the textural complexities outlined above. The grab samples were, by necessity, widely spaced. Accordingly the following simple textural parameters were used: gravel-sand-mud ratio, % lithic gravel, % shell gravel, % mud, and grain-size modes within the sand range.

The gravel-sand-mud ratio, including a provision for shell gravel content, was determined for each grab sample and used to construct a simple sediment distribution map. The remaining parameters form part of a "quick" modal analysis which was used with some support from sediment colour (*see* p. 31) to map the principal sediment populations. Since grain-size modes tend to retain their integrity despite changes in transport energy or mixing with other sediment, they are an effective means of tracing discrete sediment populations with different spatial and temporal relationships through this complex zone of modern, relict and palimpsest sediments (*cf*. Curray 1961).

SEDIMENT MAP

The method used to construct the basic surficial sediment distribution map (Fig. 10) conforms fundamentally with that used by the N.Z. Oceanographic Institute, which is a modified form of the Folk (1968) method. However, the calcium carbonate content of the sand and mud was not differentiated since the terrigenous content is dominant in all the samples. The method of map construction is as follows:

Two separate maps are contoured:

1. Gravel in the total sample at 80%, 30% and 5% by weight, and percentage carbonate in the gravel at 50%.
2. Sand in the fraction < 2 mm at 90%, 50% and 10% by weight.

When combined on one map (Fig. 10) the intersecting contours define areas occupied by particular grain-size classes. In areas where sample coverage is lacking (off the Ashburton River and south of Timaru) sediment boundaries were interpolated from Hydrographic Chart notations and are hence subjective.

Gravel

Gravel occurs in four areas and is, with few exceptions, dominantly lithic. It is found mixed with mud off the Motunau coast in the extreme north-west of the area. Further south it occurs between the Rakaia and Rangitata Rivers, within 25 km of shore, with variable amounts of mud and sand as minor constituents. South of approximate latitude 44° 30′S it is found in a coastal belt 5–10 km wide that extends south of the Waitaki River. On the outer shelf, a diffuse and patchy zone of gravel and gravelly sediment

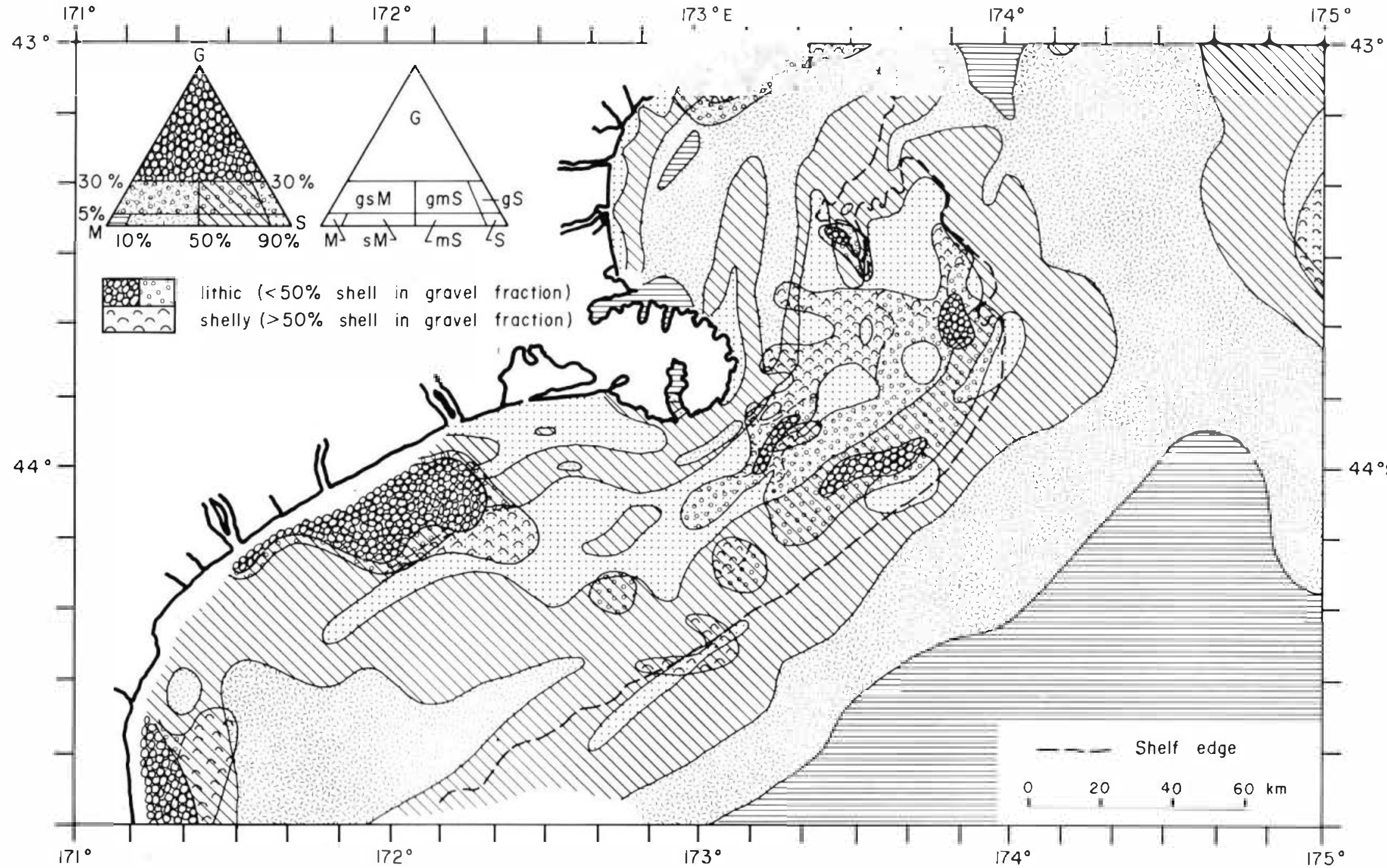


FIG. 10. Surficial sediment distribution on the Canterbury continental shelf.

extends from Pegasus Canyon to about 44° 20′S. The highest gravel concentrations occur where the shelf is narrowest south-east of Banks Peninsula.

Gravel is absent from most of Pegasus Bay, from a narrow belt around and immediately adjacent to Banks Peninsula, from the far northern part of Canterbury Bight, and from the southern part of the Bight (except the coastal belt south of Timaru).

Sand

Sand is almost ubiquitous on the shelf. It is present in quantity in all but the muddiest areas. Clean sand occurs along the coast of Pegasus Bay as a near-shore belt about 4 km wide; and in a 13 km wide coastal zone in northern Canterbury Bight. It also occurs as a prominent lobe that projects northwards from Banks Peninsula into Pegasus Bay.

Clean sand also occurs, locally mixed with gravels, in a zone on the middle shelf. North-east of Banks Peninsula this clean sand zone extends right out to the shelf edge and into Pegasus Canyon; south-west of Banks Peninsula it extends into Canterbury Bight where it is gradually and unevenly replaced south-westwards by muddy sand and sandy mud. A belt of muddy sand occurs along the south-eastern margin of this zone, separating it from the shelf edge.

Isolated areas of clean sand form a chain along the shelf break from end to end of the study area.

Mud

Mud with less than 10% sand is rare on the Canterbury continental shelf. Sandy mud is found in a large patch on the middle shelf at the southern end of the area. It grades laterally landwards, seawards and northwards into muddy sand. Its southern limit is unknown.

Most of Pegasus Bay is covered by sandy mud which extends north of Banks Peninsula in a broad band. Mud with less than 10% sand is confined to the deeper northern part of the bay and to a small patch at the southern end adjacent to Banks Peninsula. It is also found within the bays of Banks Peninsula. It grades laterally landwards and seawards into muddy sand. Within the sandy mud zone in Pegasus Bay is the tongue of sand which was described above. The northern limit of the sandy mud is beyond the boundary of the study area at approximate latitude 42° 52′S (Cullen & Gibb 1966). The zone extends south around Banks Peninsula as a very narrow intermittent band 6 km off-shore which then trends west into Canterbury Bight. Mud less than 10 cm thick, overlying muddy sand, was sampled off the Rakaia River mouth.

Beyond the edge of the continental shelf, the mud content of the sediment increases and most of the slope is covered with sandy mud and mud. The sediments become more calcareous with increasing distance from the shelf. Sandy mud and mud are common at the bottom of the submarine canyons off Pegasus Bay. The mud distribution is shown in Fig. 11.

DISTRIBUTION OF MODES

Runs of complete $-4\ \Phi$ to $+4\ \Phi$ size analyses on a representative number of samples defined the major modal classes in the gravel/sand range. These modes were sufficiently well separated to be easily read from histograms. They are:

Mode I – gravel (excluding shell gravel) $-4\ \Phi$ to $-1\ \Phi$
Mode II – medium sand $1.1\ \Phi$ to $1.4\ \Phi$
Mode III – fine sand $1.9\ \Phi$ to $2.6\ \Phi$
Mode IV – very fine sand $2.9\ \Phi$ to $3.4\ \Phi$

Shell gravel is present in sufficient amounts in many samples to form a gravel mode. It defines areas of relict sediments (low present-day sedimentation) or areas of active erosion. The parameter "weight % shell gravel" (as a function of total sediment weight) has been accordingly treated as a mode.

Lithic gravel also indicates areas of active erosion or low present-day sedimentation on the shelf, and is significant for indicating past near-shore environments. Its concentration is expressed as weight % gravel in the sediment after removal of shell gravel.

In many places, mud is the dominant sediment. Although pipette analyses of the mud fraction were not done as a matter of routine, samples that were so analysed contained a mode ranging from $4.5\text{-}6.5\ \Phi$ (coarse to medium silt). For the purposes of this study the sizes within the mud range are not differentiated. Because extremely polymodal sediments are the rule rather than the exception on the continental shelf, the mud content is considered here to be a more reliable indicator of the energy of the environment than the standard deviation of grain sizes (sorting). A low mud content in the sediment is taken here to imply a high energy environment.

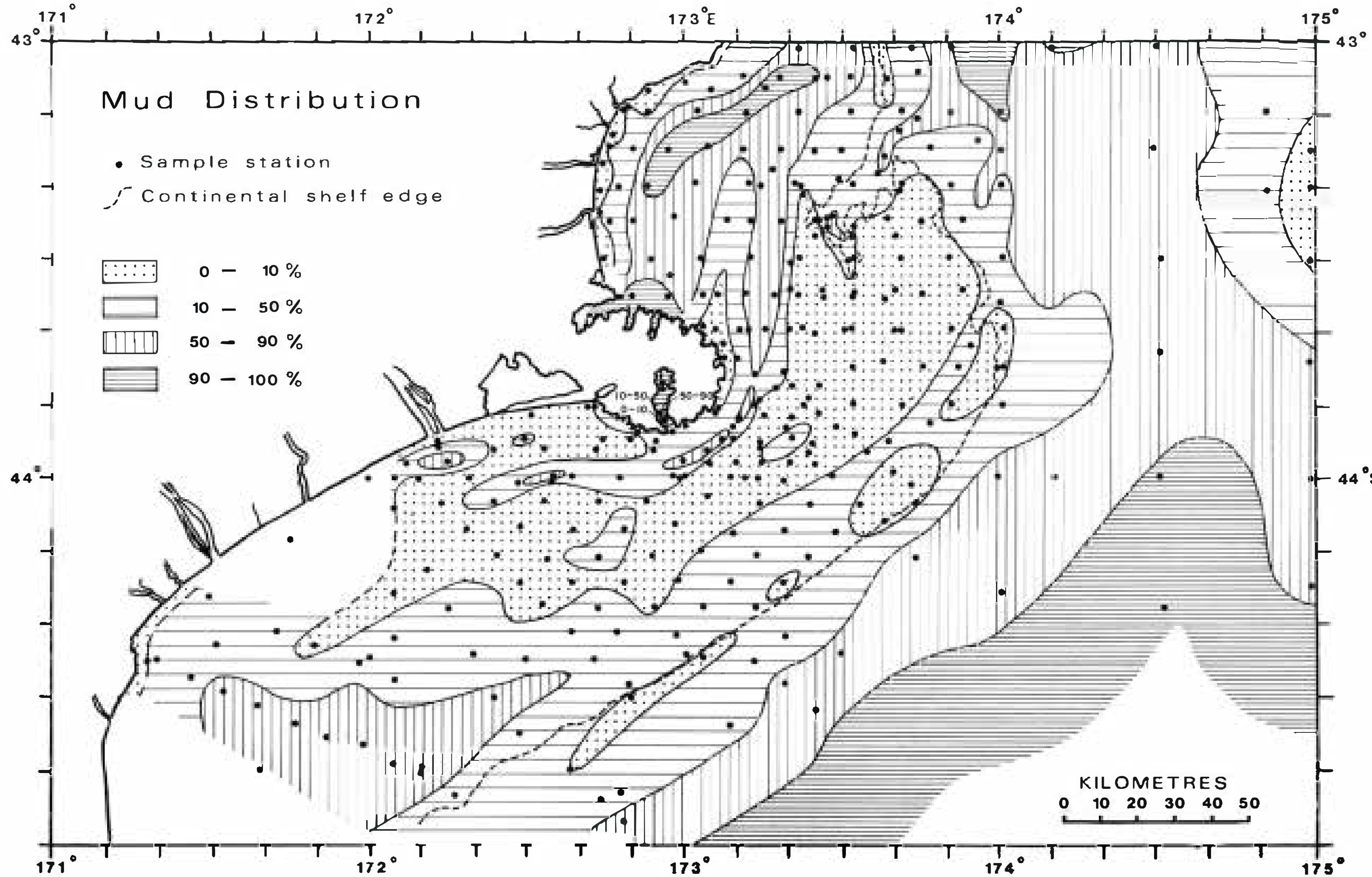
Lithic Gravel (Mode I) Distribution

The lithic gravel content of the sediment is calculated thus:

$$\text{wt lithic gravel} \div (\text{wt total sediment} - \text{wt shell gravel}) \times 100$$

The results are contoured at 0.1%, 2%, 5%, 10%, 20%, 40% and 80% in Fig. 12.

This figure is a truer portrayal of the relict gravel distribution than Fig. 10 because shells, which include a modern as well as a relict population, are excluded from the calculation. The 0.1% contour is used to detect the slightest presence of gravel in the surface sediment as this may indicate the presence of shallow underlying gravel beds and help to give a more complete picture of the former extent of gravel deposits on the shelf. The gravel south of 44° 30′S off the Waitaki River is not included here as its presence is only known from notations on the N.Z. Hydrographic Chart (Hydrographic Branch, Royal N.Z. Navy) which are not quantitative. Lithic gravel is distributed right across the muddy shelf at the northern end of the study


Mud Distribution
Sample station
Continental shelf edge
0 — 10 %
10 — 50 %
50 — 90 %
90 — 100 %
KILOMETRES
0 10 20 30 40 50
171°
172°
173°E
174°
175°
43°
44°
44°S
171°
172°
173°
174°
175°

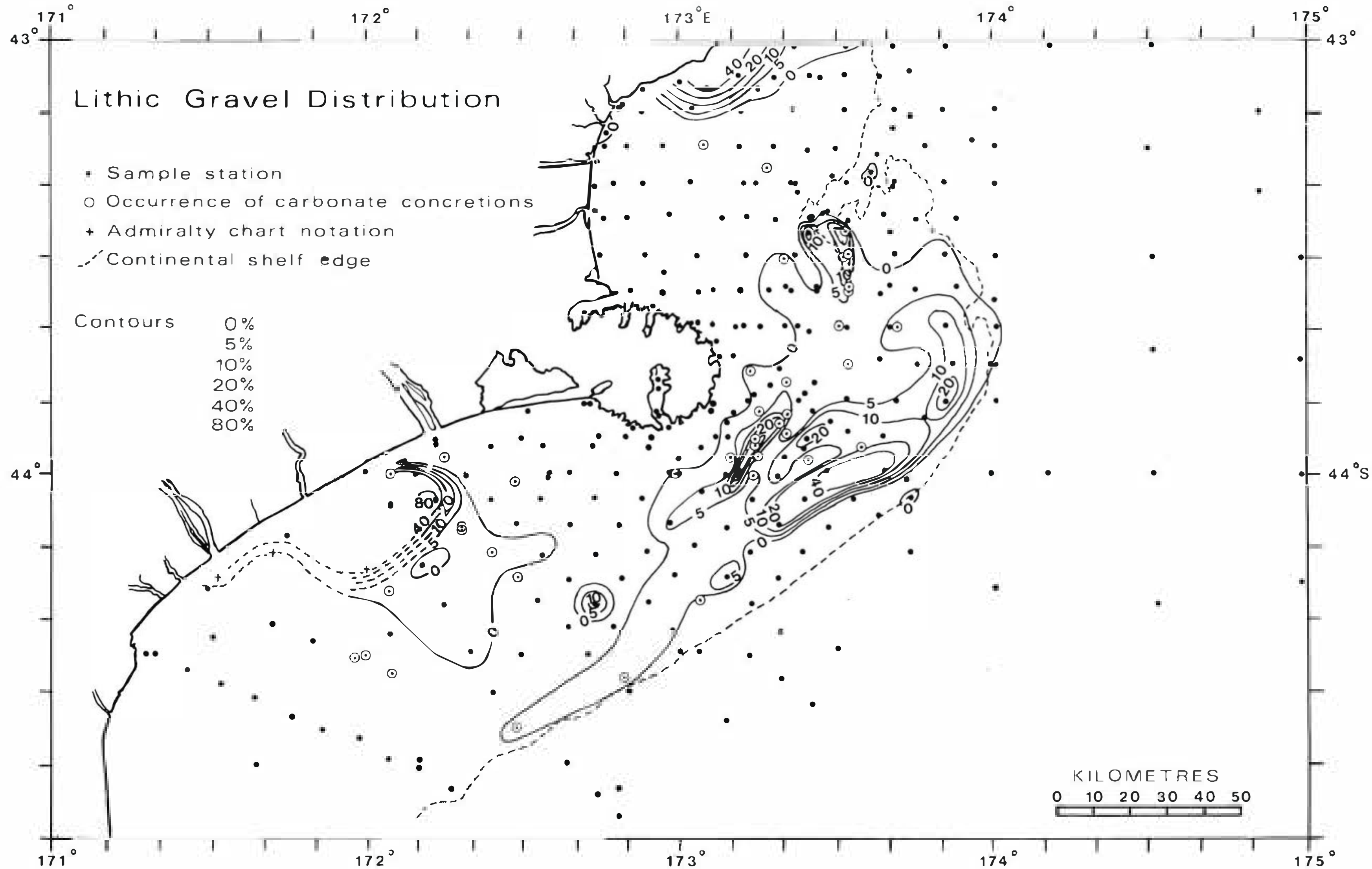


FIG. 12. Lithic gravel distribution on the Canterbury continental shelf. (Shells excluded from calculation).

area, and the lithic gravel zone in Canterbury Bight extends in a lobe to two-thirds of the way across the shelf. Off Banks Peninsula, gravel is found over most of the width of the shelf and is concentrated in three linear bands roughly parallel with the trend of the shelf. The largest extends along the shelf for about 90 km (about 10 km inside the shelf edge) from just north of Pukaki Canyon at 43° 35′S to 44° 15′S south-east of Banks Peninsula. It continues as a trace of gravel as far south as 44° 40′S. The other gravel bands are shorter (40 km and 30 km) and occupy mid-shelf positions on the narrowest part of the shelf directly adjacent to the peninsula.

Shell Gravel Distribution

The shell gravel content is calculated thus:

$$\text{wt shell gravel} \div \text{wt total sediment} \times 100$$

The results are contoured at 1%, 2%, 4%, 8% and 16% in Fig. 13.

The most obvious feature of the shell gravel distribution is its broad correlation with the lithic gravel areas. Even some of the minor trends within the lithic gravel are reflected in the distribution of shell gravel. The clearest correlations are those of the zone fringing the inside of the continental shelf edge and the more westerly of the two narrow bands of high gravel concentration on the middle shelf off Banks Peninsula.

Some relatively high shell concentrations do occur where gravel is absent or rare. A large, isolated, two-pronged patch of 1–4% shell gravel occurs in the southern part of Canterbury Bight in the muddy sand that separates the mud at the south end of the Bight from the sand of the central part. The sand of the central Bight, which contains only a trace of lithic gravel, has a shell content locally as high as 23% though generally less than 8%. This zone of high shell concentration runs directly seaward from the lithic gravel zone south of the Rakaia River.

Concretions

Concretions occur frequently in areas of high shell concentrations (Fig. 13, *cf.* Fig. 12). Even where most common, they account for less than 1% of the sediment. They consist of gravel, sand, mud and shells cemented with calcium carbonate, the sand having moulds from which shells have been partly or wholly dissolved away. The calcium carbonate cement is assumed to have come from the dissolved shells. Concretions were not included in the textural or petrological analyses because of their very special environmental significance.

Sand (Modes II, III and IV) Distribution

Distinction of Sand Modes

The distribution of significant sand modes is simple and has been combined in Fig. 14. The modes were picked to the nearest class midpoint from the histograms of the analysed samples (Herzer 1977, Appendix 3).

Mode II (1.1 Φ to 1.4 Φ – medium sand) occurs infrequently, forms a very small fraction by weight of the sample, and is in a size range that is largely contaminated by shell fragments. It occurs in association with Mode III usually where high concentrations of lithic gravel prevail but is not detectable in hand specimens. Its distribution has therefore not been separately mapped and its presence, where detected by sieve analyses, is noted on Fig. 14 by a circle.

The two most abundant modes, Mode III (1.9 Φ to 2.6 Φ – fine sand) and Mode IV (2.9 Φ to 3.4 Φ – very fine sand) can be distinguished in hand specimens by their grain size and dry sand colour, the correlation between colour and grain size being established by over 100 sieve analyses. The colours of the dry sands are olive brown (5Y 5/2–5 to 5Y 6/2–4) for Mode III and greenish grey (10Y 6/2 to 5GY 5–6/1) for Mode IV. By comparing the texture and dry colours of the unanalysed sand samples to those of the analysed series, the presence or absence of Mode III and/or IV in the former was indicated. In samples where uncertainty existed, the sample was analysed by 0.25 Φ sieving. In all, 139 samples were mechanically analysed and 191 were visually appraised. Sand colour was determined only for samples collected by the author, since suitable dry sand samples were not available in the NZOI collection and wet samples were subject to possible colour alterations during long-term wet storage.

There is a suggestion in the statistical grain-size data that Mode III, which covers a relatively wide range of grain sizes, consists of at least two sub-modes. The sub-modes are indistinguishable both petrographically and in hand specimens, and, when plotted individually, their areal distribution is rather random within the larger envelope of Mode III occurrences. For this reason the sub-modes are not treated as significant modes in this study.

Distribution of Modes III and IV

Except in very muddy areas, such as central Pegasus Bay and southern Canterbury Bight, which rarely contain a mode in the sand range, Modes III and IV, considered together, cover the shelf. Each mode has its own region, with some marginal overlap (Fig. 14).

Mode III occurs primarily in the widespread belt of sand and gravel that occupies the middle and outer shelf around Banks Peninsula. It is also found in the north-west corner of Pegasus Bay and on the inner shelf of central Canterbury Bight. It is closely associated with Mode I (lithic gravel) and shell gravel, but its occurrence is not restricted to high concentrations of gravel. It is common in upper Pegasus Canyon and on the upper continental slope opposite Mernoo Saddle.

Mode IV is found in coastal Pegasus Bay, in outer Pegasus Bay, and northernmost Canterbury Bight, in a thin band around Banks Peninsula, in southern Canterbury Bight, in a long belt just inside the shelf

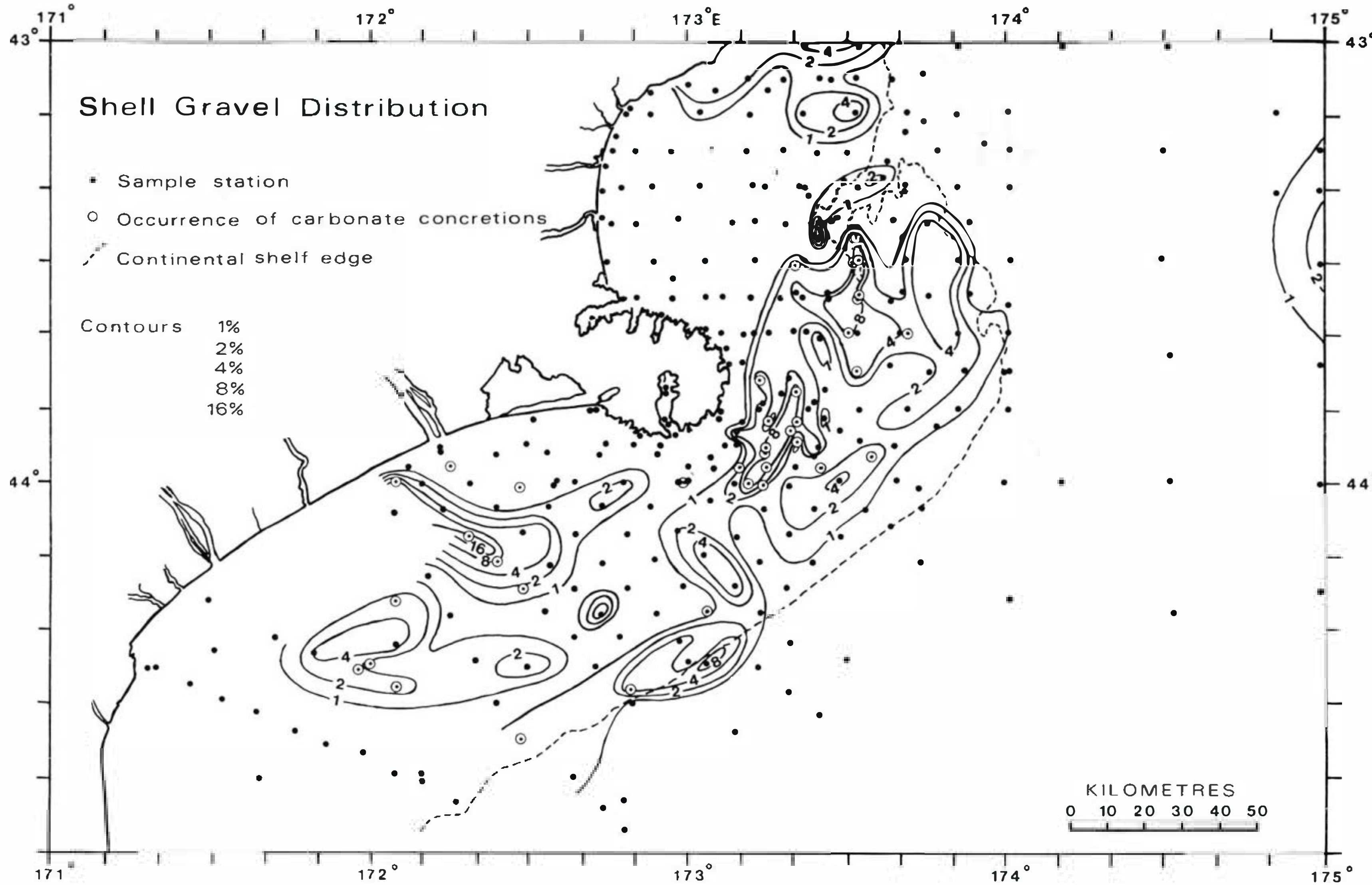


FIG. 13. Shell gravel distribution (as a function of total sediment weight) on the Canterbury continental shelf.

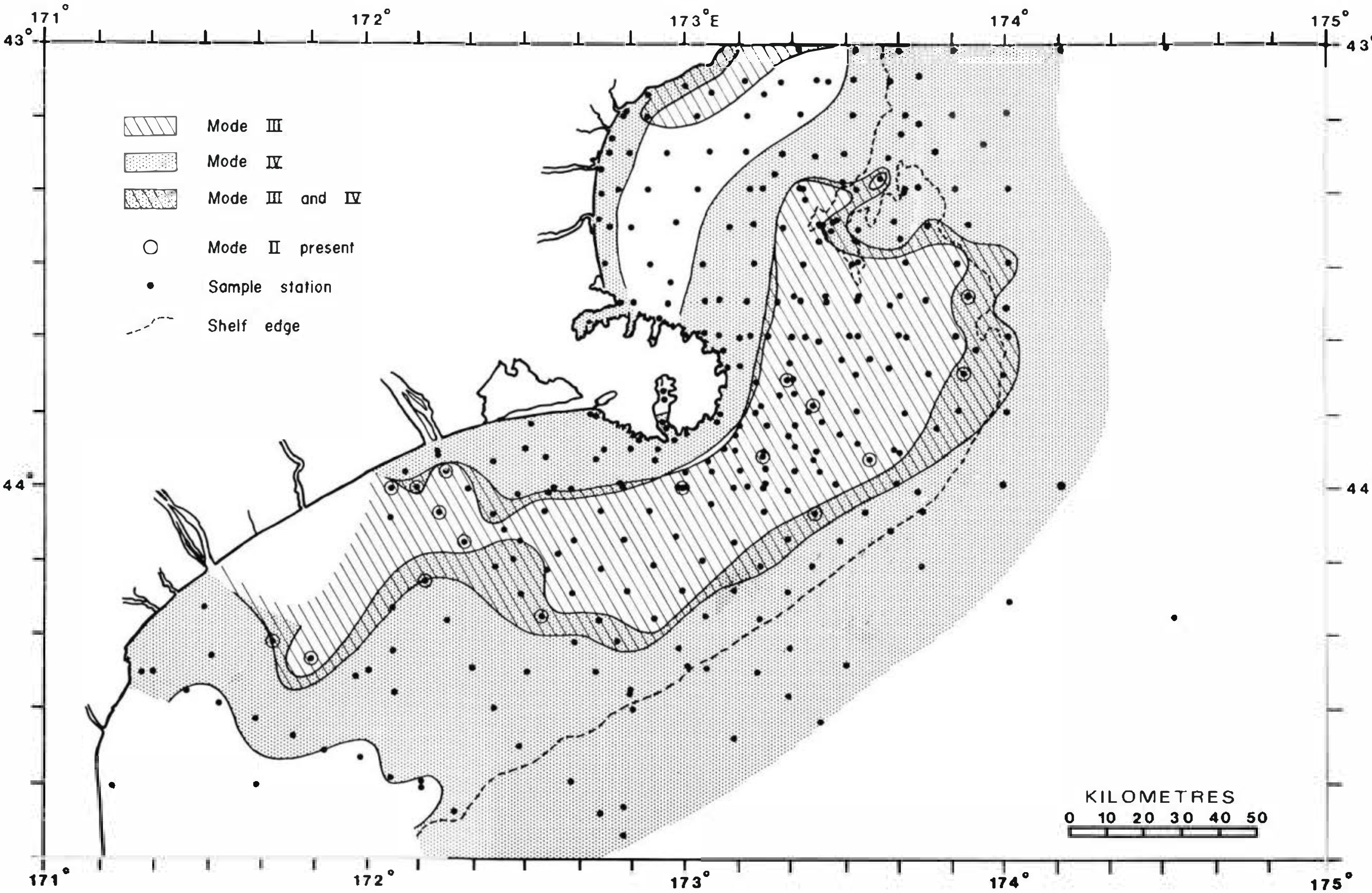


FIG. 14. Distribution of sand modes on the Canterbury continental shelf.

break, on the whole upper continental slope, and in Pegasus Canyon. Mode IV is usually associated with greater or less amounts of mud, and, except in zones of mixing with Mode III, it is generally free of lithic gravel. High shell concentrations occur with this mode at a few places.

SOME SURFACE FEATURES OF THE SEDIMENT

Side-scan sonar and underwater camera observations were made of *in situ* sediments in the zone of strong currents off Banks Peninsula.

It was found that the steeply sloping band of Zone A, Mode IV silty sand that hugs the coast of Banks Peninsula is featureless on the sonographs, being of uniform texture and having no bedforms high enough to cast a sonic shadow at the scale used. Fig. 15a shows gravel or rock outcropping locally through the featureless sand off Steep Head, Banks Peninsula. In this zone the water is mostly too turbid for photography.

In the zone of second-order ridges off Banks Peninsula (Zone D, Mode III sand, gravel and shell) sand ribbons are conspicuous and abundant (Fig. 15b) (*cf.* Kenyon 1970; Belderson *et al.* 1972). Indistinct sand waves with crest-to-trough amplitudes of 0.3–0.4 m and wavelengths of 20–30 m were locally observed, especially on the peripheries of sand ribbons. In addition there are some gradual textural changes, shown on the sonographs by a gradual lightening or darkening of the background, and some sharp interfingering contacts, the fingers being parallel to the trend of the sand ribbons (Fig. 15c). The textural distinctions of the side-scan sonographs probably represent fine sand (Mode III) moving across shelly sandy gravel.

The sand ribbons, which are current-parallel structures, trend roughly parallel to the strike of the second-order ridges, i.e., north-east to north-north-east. The axes of the sand waves, which are current-normal structures, trend at high angles to the long axes of the ribbons and ridges. Sand ripples in bottom photographs (Stn H423) have east-west long axes and undetermined symmetry. With the data to hand, no preferred location of the ribbons or sand-waves with respect to the ridges (on crests, on flanks or in troughs) was found, but it is clear that currents on the bottom act in a general northerly or southerly direction.

ORIGIN OF THE SEDIMENTS

Provenance of the Gravel

The gravel on the outer continental shelf is almost exclusively of pebble and granule size, the size commonly referred to as "pea gravel". Clasts larger than $-4\ \Phi$ (16 mm diameter) are uncommon and most have diameters less than $-3\ \Phi$ (8 mm). The gravel of inner Canterbury Bight however, tends to be large. Diameters of $-3\ \Phi$ (8 mm) to $-5\ \Phi$ (32 mm) predominate. All the gravels are rounded to well-rounded (as defined by Powers 1953) and tend to be dominantly spherical to rod-shaped. The rare pebbles larger than $-5\ \Phi$ (32 mm) in diameter are frequently disc-shaped but their rounding is good.

Two suites of rock contribute to over 90% of the gravel in the samples – greywacke and quartz (Tables 1, 2; *see* Fig. 9 for sample locations). Pebbles designated as greywacke in the table include unmetamorphosed sandstones (generally of greywacke type) and argillite. The quartz pebbles are composed of massive quartzite, foliated micaceous and chloritic quartzite, vein quartz, and vein or lenticle quartz with adhering schistose wall rock. The quartz pebbles are usually iron-stained to a bright orange.

Schist occurs as a rare but persistent rock type in the gravels. It includes schist, phyllite and foliated sandstone or semischist, usually of greywacke origin, showing lenticular streaks or deformed grains. Other rocks present in the gravels are rare and occur sporadically. They include chert, felsite, intermediate and basic volcanic tuff, porphyry and scoria, orthoquartzite, jasper, agate and indeterminate rocks.

When the relative proportions of greywacke (including argillite) and quartz in the $-3\ \Phi$ to $-2\ \Phi$ (4–8 mm) fraction of each sample are plotted on a map, a clear-cut pattern emerges (Fig. 16). The size fraction chosen is the largest one that provides a sufficient number of pebbles to make a valid plot of the distribution.

Close to shore, the gravel is almost entirely greywacke, while on the middle and outer shelf the gravel is a mixture of greywacke and quartz. At mid-shelf, off Banks Peninsula, there is an elongate zone of gravel that is particularly rich in quartz.

Only 15 samples contained enough gravel larger than $-3\ \Phi$ (8 mm) to be useful (Table 2). The ratio of greywacke to quartz in them is generally higher than in the smaller sizes but the distribution pattern is otherwise unaffected.

The rare pebbles composed of rocks other than greywacke and quartz consist of rock types that outcrop on the eastern side of the South Island but do not provide any useful data on source areas.

However, different source areas can be determined for the greywacke and quartz. The gravel will have come from the eastern side of the South Island opposite the study area, and also because of the general north-eastward drift, from some distance to the south; that is from about latitude 43° S to the southern end of the South Island.

The bedrock geology of the South Island is shown in Fig. 2. In Canterbury, south to latitude 45° S, it is almost entirely greywacke; and in Otago, from latitude 45° S to latitude 46° S, it is almost entirely schist. The boundary is gradational and it is generally accepted that the schist is metamorphosed greywacke and argillite. Quartz occurs as veins in the greywacke but is

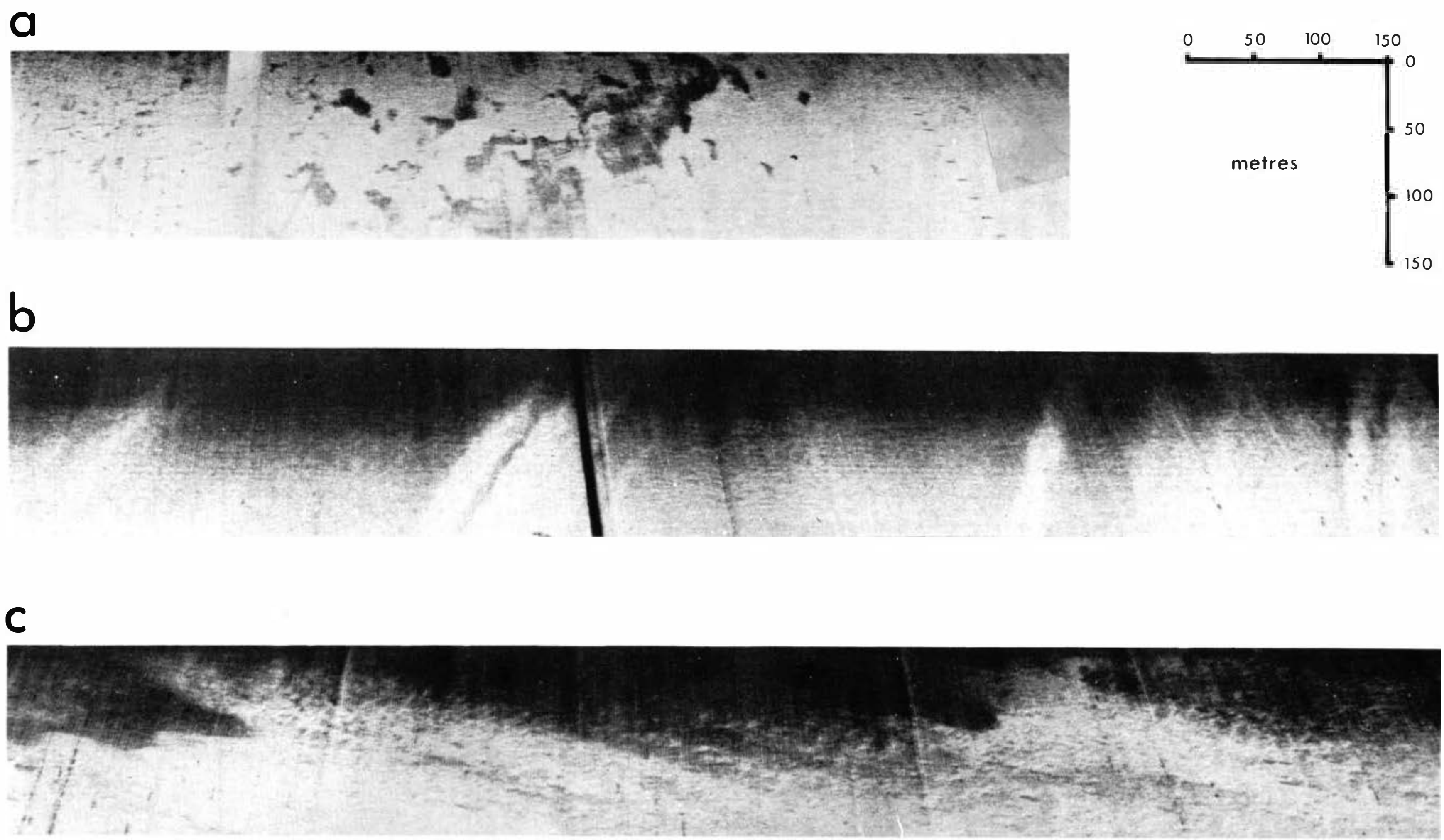


FIG. 15. Side scan sonographs of the shelf off Banks Peninsula. *See* Fig. 6 for locations.
(a) Gravel or outcrop of volcanic rock surrounded by very fine, silty Mode IV sand off Steep Head, Banks Peninsula.
(b) Sand ribbons in relict Mode III sand and gravel. The dark areas are sandy, shelly gravel and the light areas are fine sand.
(c) Sand ribbon-like interfingering contacts between fine Mode III sand (light) and sandy, shelly gravel (dark). Sand waves trending obliquely to the ribbon trend are faintly visible.

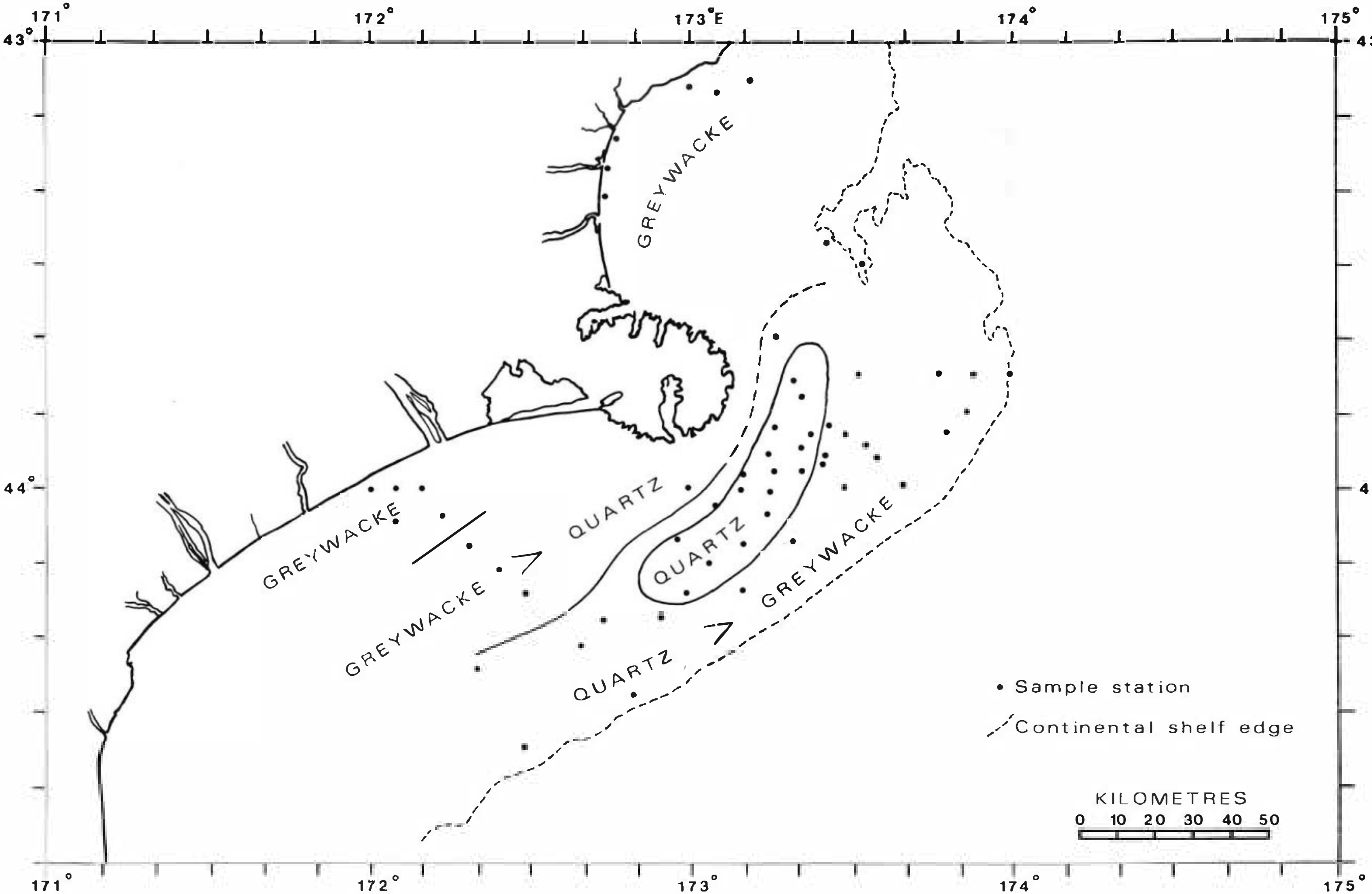


FIG. 16. Distribution of the dominant rock types in the -2Φ to -3Φ gravel fraction. The greywacke field contains more than 90% greywacke (+ argillite). The quartz field contains more than 90% quartz. The mixed areas are subdivided according to the relative proportions of the two rock types.

particularly abundant in the schist; there is no other evident bedrock source for the quartz. There is no lack of quartz gravels that have been derived from the schist (*see*, e.g., Gage 1957, Speden 1971, Andrews 1973); they occur as Upper Cretaceous to mid-Cenozoic strata resting on the schist, as Quaternary gravels in river valleys draining the schist, as Holocene and present-day beach gravels along the Otago coast, and as relict gravels on the continental shelf of Otago from the Clutha River (46° 20′S) to the Otago Peninsula (45° 45′S). There are no corresponding quartz gravels derived from the greywacke.

The greywacke and the quartz of the Canterbury shelf thus appear to be derived from two separate sources. The greywacke must have come directly from the rivers draining the greywacke region to the west. Features of the quartz gravels, however, indicate a schist provenance for the quartz; schist is present in small amounts in most of the quartz gravels but is absent in the greywacke gravels and much of the quartz is itself clearly schistose.

The relative lack of greywacke pebbles on the outer shelf is explained by the profile of the Pleistocene Canterbury rivers, for example the Rakaia River (Fig. 17). The on-shore section of the profile is drawn along the crest of the Rakaia fan; the off-shore section is drawn from a 3.5 kHz seismic record and represents the closest approximation to the surface of the coastal plain during the Last Glacial maximum, free of any later sediment blanket. The profile shows that the gradient decreased very quickly about 10 km seaward of the present shore. Such an abrupt change in river gradient would be accompanied by a very rapid reduction of bed load grain size (*see*, e.g., Yatsu 1955). Thus it is doubtful that greywacke gravel from the Canterbury Plains was transported across the exposed shelf in very large quantities during the Last Glacial, most of it being deposited on the aggrading fans. Without dilution from the nearby greywacke source area, quartz gravel, transported north along shore from Otago, would have come to dominate the Pleistocene beaches of the middle and outer shelf off Canterbury. The quartz pebbles, being probably more resistant than greywacke pebbles, may have been further concentrated by high energy beach and near-shore processes. This is suggested by the presence today of the quartz-rich gravel belt midway across the shelf off Banks Peninsula, which may have originated through present or past reworking.

The absence of quartz pebbles on the inner shelf is probably due to two factors operating towards the end of the deglacial transgression:

1. the establishment of the rugged coastline of Otago with its flooded embayments and headlands which would have halted the northward flow of quartz gravel;
2. the greatly increased supply of greywacke from cliff erosion of the Rakaia and Rangitata fans and the Waitaki fan (44° 50′S – 45° 05′S) to the south, and from downcutting of the river beds as the local ice retreated and the sea advanced.

There is a profound lack on the shelf of gravel attributable to erosion of the Banks Peninsula

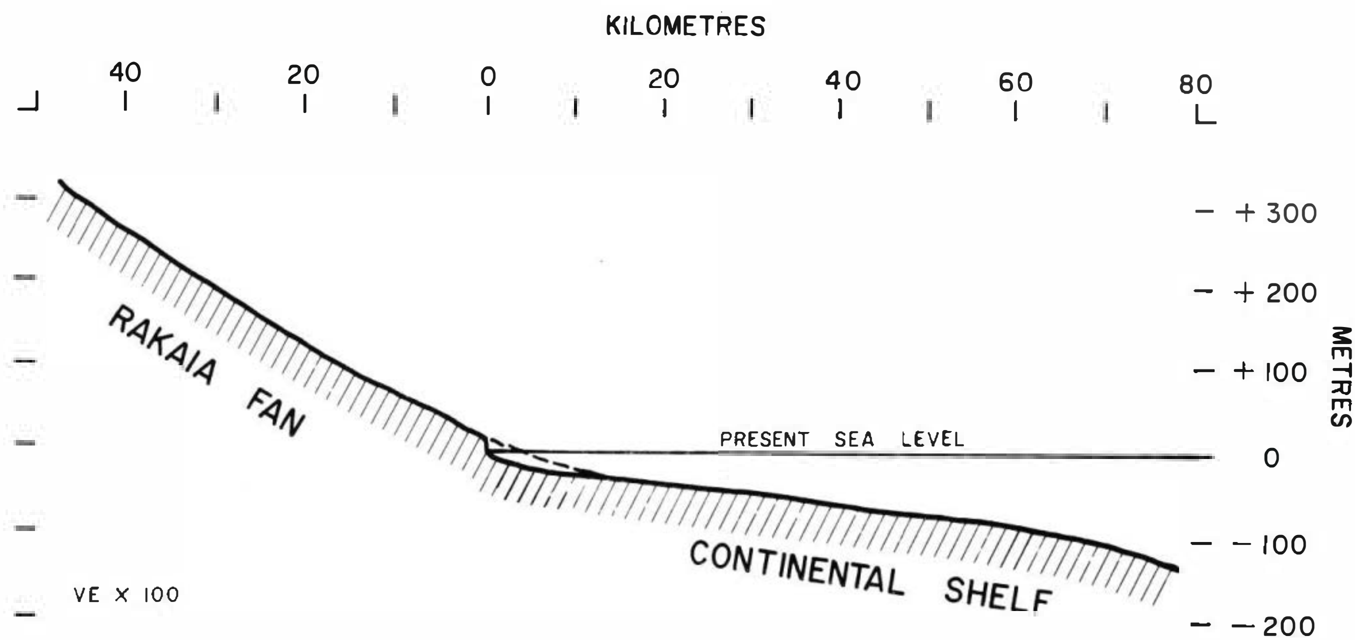


FIG. 17. Gradient profile of the crest of the Rakaia fan surface (Canterbury Plains) and the adjacent continental shelf stripped of modern sediment. *See* Fig. 1 for location of profile.

volcanics. This is probably due in part to the embayed coastline of the peninsula whch prevents river-borne gravel and even sand from reaching the open coast; and in part to the much greater resistance to wave attack of the peninsula's vertical lava cliffs compared to that of the cliffs of unconsolidated Pleistocene alluvium along the adjacent Canterbury coast.

Provenance of the Sands

The sand grains on the continental shelf in the present area range from very angular to well-rounded (as defined by Powers 1953). They are in general better rounded than those in the modern river beds and in the sea cliffs of Pleistocene river alluvium. The degree of rounding tends to increase with grain size. Hence, Modes III and II sands are better rounded than the finer Mode IV sands. Modes II and III contain a large proportion of iron-stained sand grains which Mode IV does not. Both these facts could suggest a separate provenance for each mode. However, Emery (1965) and Judd *et al.*(1969) have stated that a yellow surface rind may be acquired during Pleistocene subaerial weathering, and Swift & Boehmer (1972) have suggested that yellow colour can be simply a function of grain size in marine shelf sands, the depositional environment of the coarser sands tending to be more agitated and therefore more oxygenated than the environment of deposition of the finer sands. That larger sand grains are often better rounded than smaller ones is well known.

The mineral composition of grain size fractions representing the different modes from various places on the shelf was determined petrographically. The fractions were selected from samples containing only unimodal sand populations in order to avoid the possibility of contamination from the tail of an adjacent population. As a rule, approximately 200 grains were identified in each thin section but in several slides of poor quality, only about 100 grains could be identified. Potassium feldspar was distinguished by staining with sodium cobaltinitrite (Bailey & Stevens 1960).

The results are presented in Table 3 (*see* Fig. 9 for sample locations). There are some consistent differences between the mineral composition of one mode and another, and in the mineral composition from one place to another. The great majority of the lithic sand grains are from sedimentary rocks (immature sandstones and mudstones) and most of the remainder are from low grade pelitic and psammitic metamorphic rocks. This is consistent with the two sources mentioned above – greywacke and schist, the greywacke being the closer source.

Sedimentary rock fragments are relatively abundant in Mode III and impoverished in Mode IV, while the reverse is true for quartz. This could reflect differences in source but it is hazardous to attempt such a correlation because in sand-size siliciclastic sediments, the ratio of quartz to lithic fragments usually increases with decreasing grain size. When the ratio of quartz to sedimentary rock fragments is plotted against distance from shore (Fig. 18) there is an apparent tendency for the near-shore sands to be more lithic than those further off shore but this trend is not altogether independent of grain size. The finer Mode IV sands are quartz-rich in both locations, with a slight tendency towards seaward quartz enrichment; the coarser Mode III sands, however, show a strong trend to lithic grain enrichment near shore. The trend of the Mode III sands is similar to that already established for the gravels (Mode I), that is, the sedimentary rock fragments tend to be most abundant on the inner shelf adjacent to their source.

Another minor compositional difference that has some significance is an anomalous concentration of glauconite in the sample from Stn H458. This sample is typical of relatively glauconite-rich sediments found in the north-western corner of Pegasus Bay. The glauconite is dark green and lustrous, closely resembling detrital glauconite found in the nearby Waipara River which drains an area containing Tertiary glauconitic rocks. It is assumed here to come from that source.

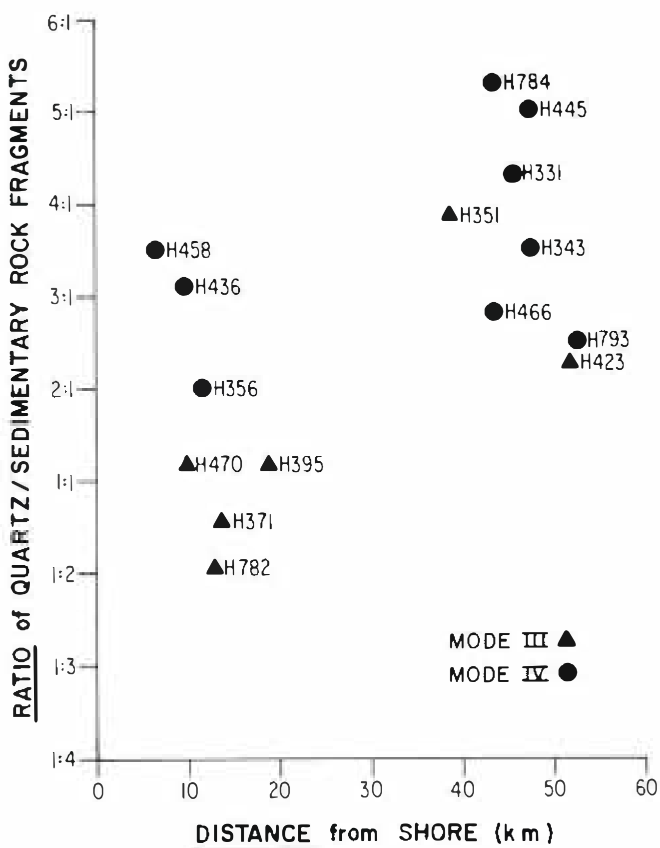


FIG. 18. Ratio of quartz to sedimentary rock fragments in the sand fraction as a function of modal grain-size and distance from shore.

The modes of the off-shore sands are about the same as the input grain size modes from the south and from the west. The spectrum of sand grain-size modes reported by Andrews (1973) on the Otago continental shelf is very similar to that on the Canterbury shelf. His modal class II (1.3–2.4 Φ), like the combined modes II and III of this paper, shows a relatively high degree of rounding, is generally iron-stained, and is associated with the gravel mode. His modal classes III (2.5–2.95 Φ) and IV (3.05–3.4 Φ) together are like Mode IV of this paper in distribution (mainly close inshore and on the outermost shelf) and in physical appearance (not iron-stained and more angular overall). Andrews concluded that all his modes, although of different ages, were derived mainly from the Otago rivers draining schist. The sands of the major Canterbury rivers and the sands associated with the Pleistocene river gravels in the coastal cliffs of Canterbury Bight have the same modal sizes as the three sand modes off shore (Herzer 1977, Appendix 3). Thus, the several grain size modes present off shore do not represent several different sources but are simply the input grain sizes, which are about the same for all the important rivers of the east coast of the middle of the South Island. In this respect, they probably reflect the weathering and mechanical break-down characteristics and original grain sizes of the South Island greywackes and low grade schists.

The Fauna

A sparse fauna, dominated by living specimens, exists on the inner shelf, while an abundant fauna, dominated by dead shells, exists on the middle and outer shelf.

The inner shelf sandy facies is dominated by *Dosinia anus, Spisula aequilateralis* and an unidentified spatangoid echinoid. *Scalpomactra scalpellum, Austrofusus glans, Amalda novaezelandiae* and unidentified holothurians, crustaceans and polychaetes are common. In the inner shelf gravel facies, *Maoricolpus roseus, Tawera spissa* and *Pulastra largillierti* are common.

The muddier facies of the near-shore and inner shelf, including the bays of Banks Peninsula, commonly contain dead *Atrina zelandica* shells (supporting barnacles and worm tubes), thickets of branching bryozoans and chitinous polychaete tubes, and wood fragments.

The assemblage of shells on the middle and outer shelf is considered to actually comprise two faunas; one relict and dating from when the sea was lower and depths shallower, and one younger and consistent with present-day water depths. The two faunas are distinguished from each other by the state of preservation of individual shells, by abundance (the younger being more abundant that the older), and by the accepted depth range of the shells. The total fauna and the accepted depth ranges of the important species are set out in Table 4 (*see* Fig. 9 for sample locations). The depth ranges are those of Powell (1961), Morton & Miller (1968), and of Rodley (1961) who summarised and evaluated depth ranges given by Suter (1913), Powell (1947, 1958, 1961), Fleming (1950), Dell (1956), Marwick (1957) and Hulme (1958).

The following is a list of the important shells that are thought to belong to the younger, deep-water fauna. They are the most pervasive species, and in contrast with the relict fauna, are well preserved.

Chlamys (Mimachlamys) subsp.; *Diplodonta globus; Nemocardium pulchellum; Notocallista multistriata; Pleuromeris zelandicus; Saccella bellula; Scalpomactra scalpellum; Tellinella charlottae; Zeacolpus (Stiracolpus) symmetricus;* the small Myadoras: *M. antipoda. M. boltoni* and *M. novaezelandiae;* and the Nuculidae: *Enucula strangei* and *Nucula strangeiformis*.

The following is a list of the important shells that are thought to belong to the older (relict) shallow-water fauna. The shells are frequently abraded, corroded, and bored.

Paphies australe; Paphies subtriangulatum; Chione stutchburyi; Pullastra largillierti; Venericardia purpurata; Myadora striata; Gari stangeri; Gari lineolata; Ostrea sp.; *Micrelenchus huttoni; Zethalia zelandica;* and the mussels – *Mytilus edulis aoteanus; Aulacomya maoriana; Modiolarca impacta* and *Modiolus* sp.

In many samples the shallow-water species are far more abundant than the deep-water ones. For this reason they are thought to have lived where they are now found, and not to be shells that have been transported across the shelf from shallow water by bottom currents or by being attached to flotsam.

Several cores taken on the middle and outer shelf in areas of shallow-water shell occurrences penetrated shell layers from 0.5–2 m below the sea bed (H403. H405, H777, H790, H810, H812 – Fig. 9). The buried shell layers contain the same fauna as that at the surface but the shallow-water species are much more abundant while the deep-water species are distinctly rarer (Table 5). Three additional shallow-water species were found in the cores: the beach dweller *Dosinia subrosea*; the coastal mussel *Perna canaliculus*; and *Glycymeris laticostata* which inhabits the inner shelf. The sediment of the middle and outer shelf, with its shallow-water shells, was evidently originally deposited during glacially lowered sea level and the upper part has been progressively mixed with younger and deeper-water shells.

STRATIGRAPHY

INSTRUMENTATION AND COVERAGE

Using an EDO 3.5 kHz profiler, a basic pattern of lines was run more or less at right angles to the coast (Fig. 7). The transducer is hull-mounted and it was possible to run the profiler during other operations and while steaming between stations. This added greatly, if not systematically, to the coverage of the area and provided abundant intersecting tie lines for the basic pattern (Fig. 4). In addition to the main survey, a series of short lines were run in the vicinity of the submarine canyons. All the original records are held at the N.Z. Oceanographic Institute, Wellington.

Because of its relatively high frequency of 3.5 kHz, the profiler has a high resolution but a fairly limited penetration. A strong echo is returned from sand and gravel, and penetration is virtually nil where these are at the surface. Mud is more acoustically transparent: reflectors are thin and clear. Penetration of 60 m or more is possible through mud. However, gas generated from decay of organic material in the mud can produce a strong reflection and limit deeper penetration (Schubel & Schiemer 1973, Keen & Piper 1976). Reflections from gas occur at places in the muddy sediments of Pegasus Bay (Profile 2, Fig. 19). Thus, certain characteristics of the sediment may reduce the penetration of the 3.5 kHz system, but this very fact makes it possible to infer sediment types from the profile.

STRATIGRAPHIC NOMENCLATURE

The Late Quaternary stratigraphy of the continental shelf is related in this paper to diachronous shelf-wide unconformities created by shelf-wide glacio-eustatic regressions and transgressions. These are related via the following terminology to the oxygen-isotope paleoclimatic-paleomagnetic record of Shackleton & Opdyke (1973) to provide a basic chronostratigraphic framework.

Deglacial:	6–18 ka B.P.
Last Glacial:	18–75 ka B.P. (Shackleton & Opdyke stages 2, 3 and 4)
Last Interglacial:	75–128 ka B.P. (Shackleton & Opdyke stage 5)
Penultimate Glacial:	128–195 ka B.P. (Shackleton & Opdyke stage 6)
Penultimate Interglacial:	195–251 ka B.P. (Shackleton & Opdyke stage 7)

Figures 19 to 23 are line drawings of the profiles located in Fig. 7 set out in order from north to south. Three major units are apparent.

The top unit (P) is a discontinuous blanket of variable thickness and is best developed on the inner continental shelf, particularly in Pegasus Bay (Profiles 2, 3, 4) and skirting Banks Peninsula (Profiles 5, 6, 8). It thinly covers the sea bed of southern Canterbury Bight (Profiles 10, 11).

The middle unit (CB), which is further subdivided into upper and lower parts (CB_U and CB_L respectively), extends over most of the shelf. It is best shown in the southern part of Canterbury Bight (Profiles 10, 11) where the top unit (P) is thin and muddy. It is relatively thin near shore and thickens seaward with well defined foreset beds that continue down the continental slope. It is bounded above and below by zones of apparent erosion, infilling and reworking which show fairly clearly in the profiles.

The lower unit (X) shows up clearly at a few places only (Profiles 1, 9, 10, 11) and is not discussed in detail.

The middle and upper units are considered to be formations and are named and described accordingly: the Canterbury Bight Formation (CB) and the Pegasus Bay Formation (P). The chosen upper and lower limits of the formations do not conform precisely to the conventions generally used in terrestrial stratigraphy, since the basal transgressive sequence is included in the underlying formation rather than in the overlying one. It is felt that the mapability of the formations would be severely restricted if normal convention had to be followed, since the basal sequence, including transgressive and palimpsest sediment, is derived from the underlying formation and is texturally and compositionally distinct from the overlying progradational sequence.

PEGASUS BAY FORMATION

Type and Reference Profiles

Profile 3 (Fig. 20) (NZOI No. 1002–18) (in Pegasus Bay) is designated as the type profile and Profile 11 (Fig. 23) (NZOI No. 1034–22) (in southern Canterbury Bight) is designated as a reference profile. Together they show most of the diagnostic features of the formation as required by the American Commission on Stratigraphic Nomenclature (1961).

Upper and Lower Boundaries

The upper surface is that of the sea floor (smooth zones A and E already described; Fig. 7). The base of the Pegasus Bay Formation is uneven, being the eroded and reworked top of the underlying Canterbury Bight Formation. The formation is thickest on the inner shelf and thins landward and seaward. The maximum thickness on a given profile in southern Canterbury Bight is only 2–7 m but the formation is much thicker in northern Canterbury Bight and Pegasus Bay, reaching a maximum of > 28 m in south central Pegasus Bay. Where the formation is thickest, its base is ill-defined on the profiles.

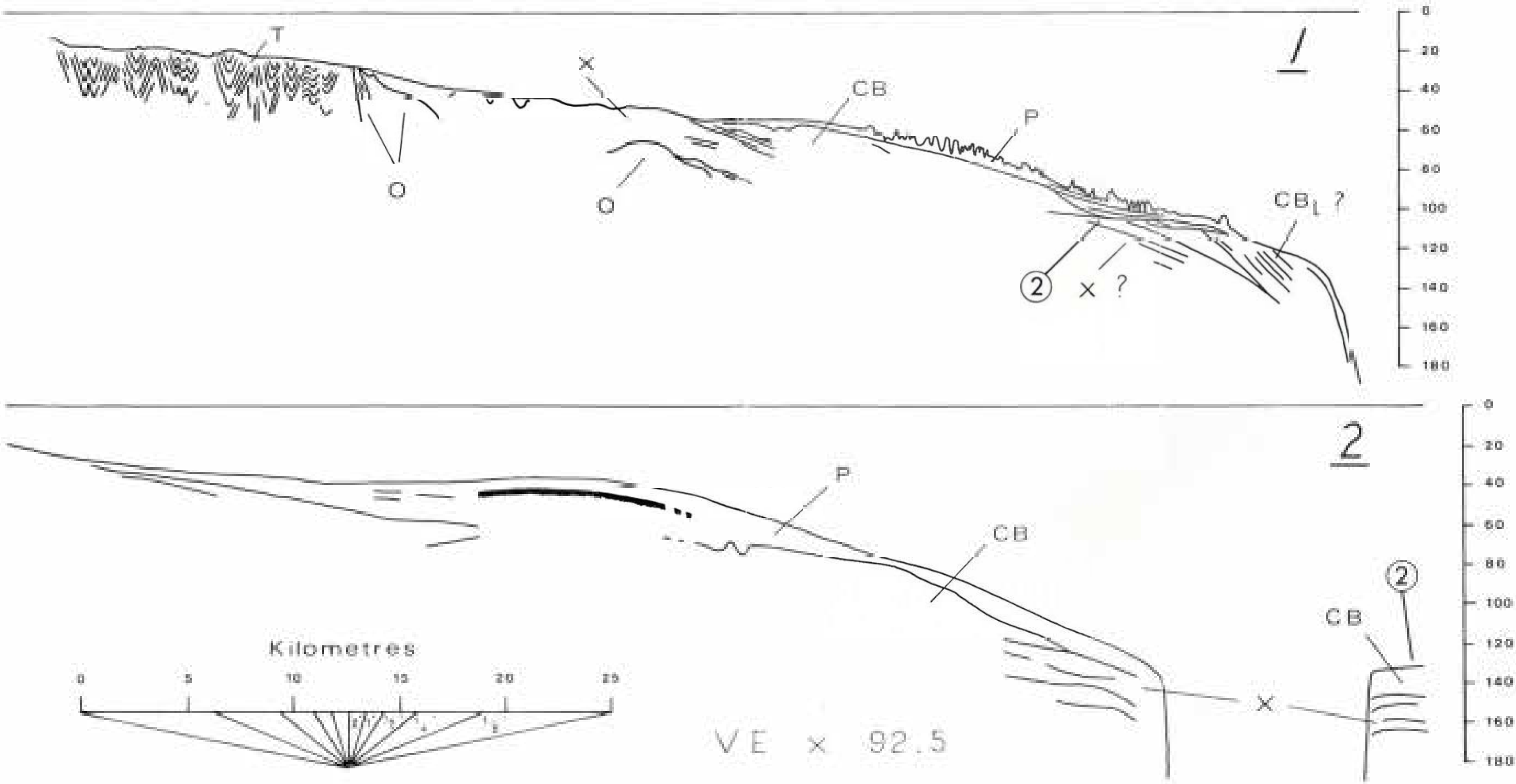


FIG. 19. 3.5 kHz seismic profiles 1 and 2 across northern Pegasus Bay. P. – Pegasus Bay Formation; CB – Canterbury Bight Formation; CB_L – Canterbury Bight Formation (lower member); X – Penultimate Glacial unit; O – Older Pleistocene units; T – Probable Tertiary rock. The strong reflector within the Pegasus Bay Formation in Profile 2 is caused by gas in the sediment. Circled numbers indicate the locations of the paleoshorelines appearing in Fig. 33. Vertical scale in metres.

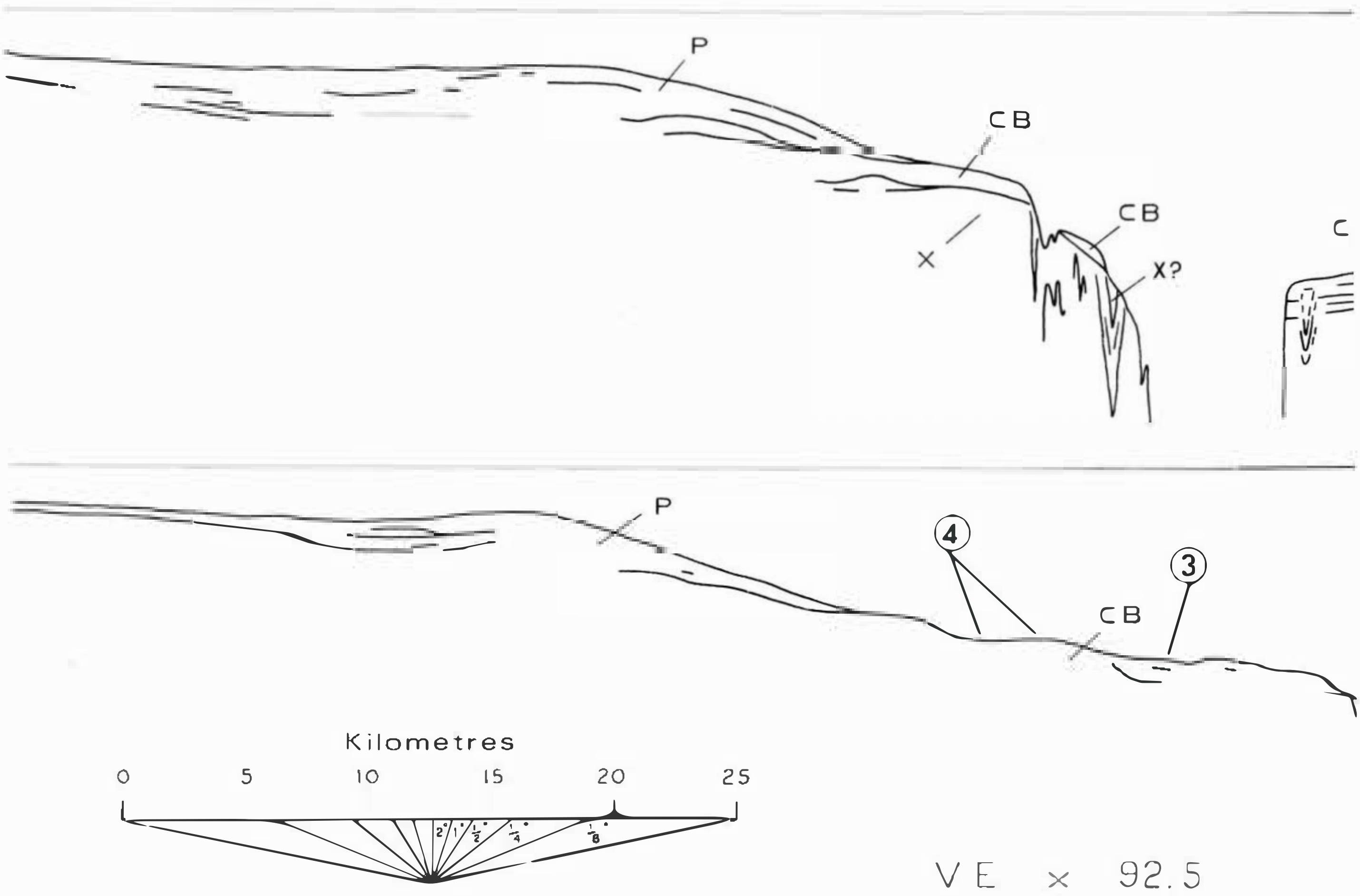
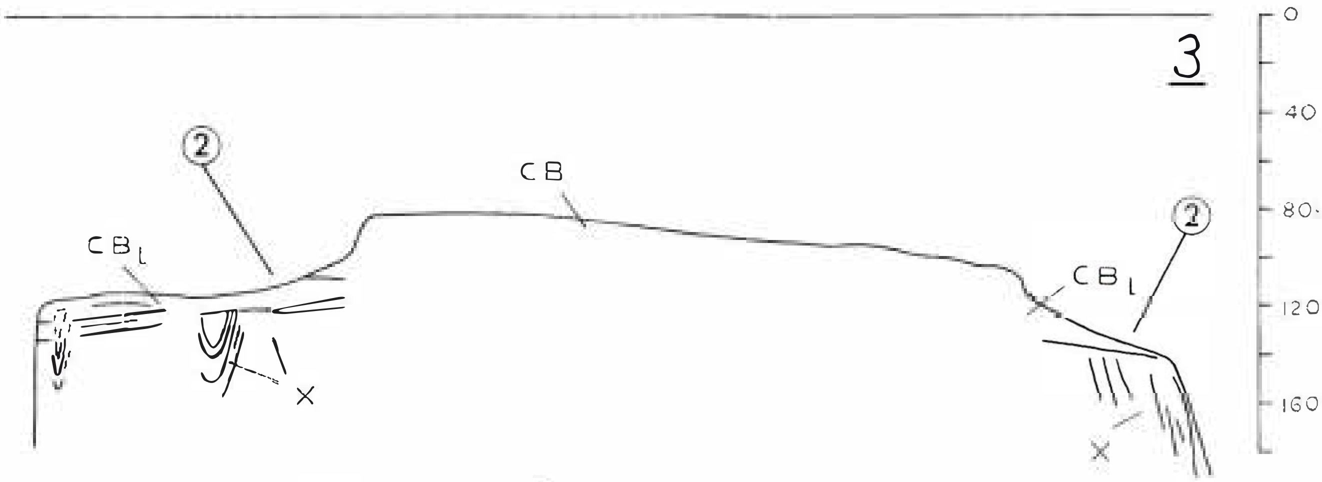
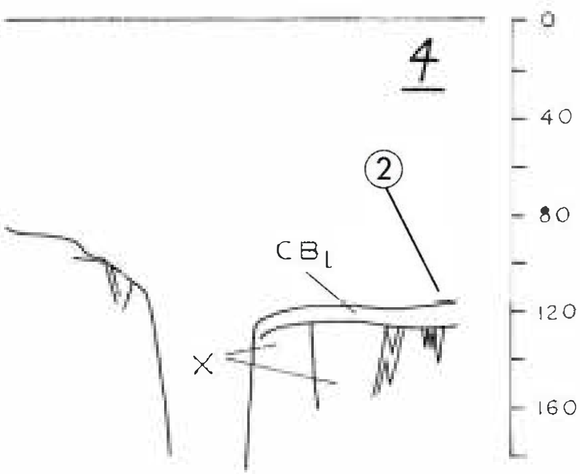


FIG. 20. 3.5 kHz seismic profiles 3 and 4 across southern Pegasus Bay. P – Pegasus Bay Formation; CB – Canterbury Bight Formation; CB_U – Canterbury Bight Formation (upper member); CB_L – Canterbury Bight Formation (lower member); X – Penultimate Glacial unit. Circled numbers indicate the locations of the paleoshorelines appearing in Fig. 33. Vertical scale in metres.


3
2
CB
CB_l
2
CB_l
X
X
0
40
80
120
160


4
2
CB_l
X
0
40
80
120
160

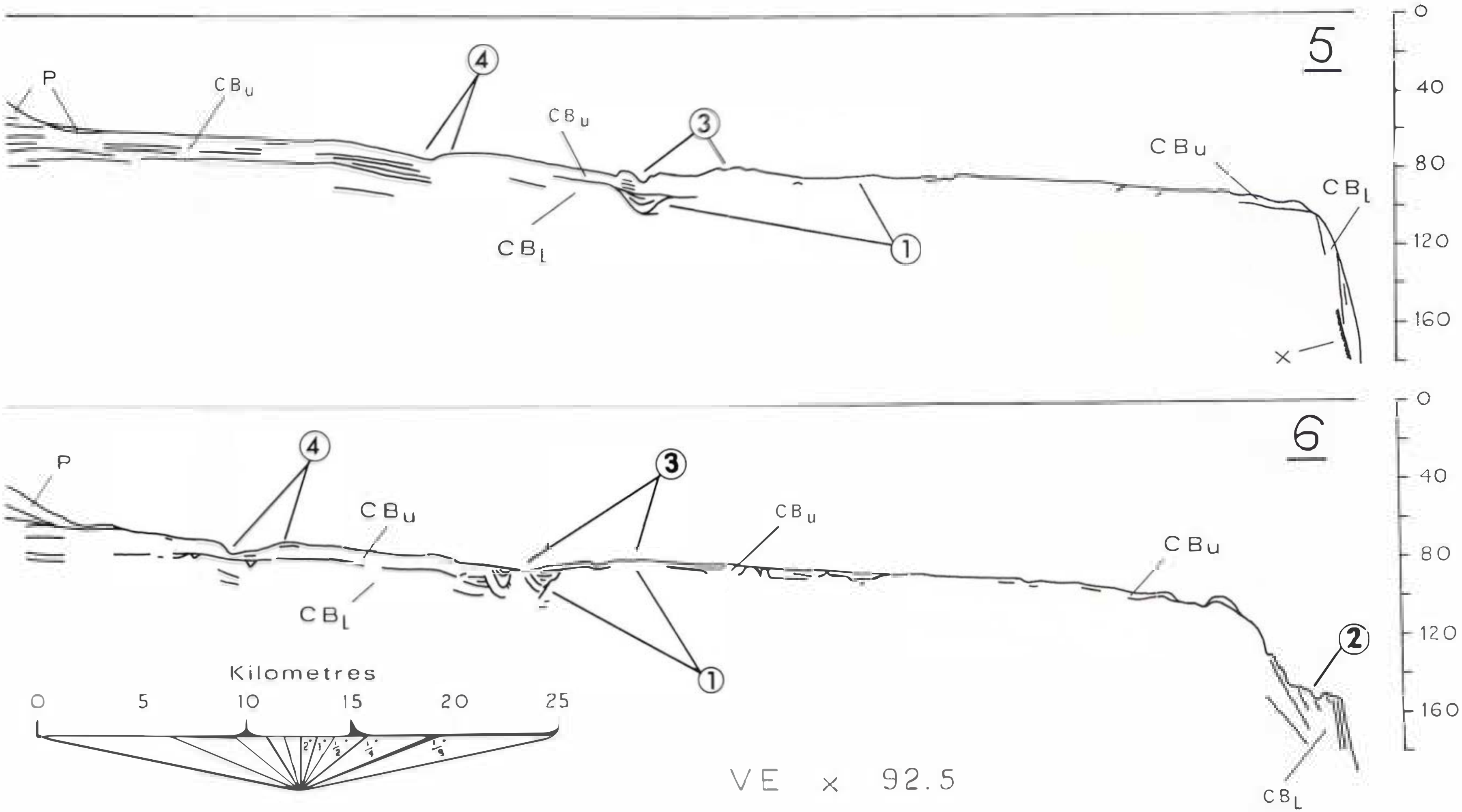


FIG. 21. 3.5 kHz seismic profiles 5 and 6 east of Banks Peninsula. P – Pegasus Bay Formation; CB_U – Canterbury Bight Formation (upper member); CB_L – Canterbury Bight Formation (lower member). Circled numbers indicate features associated with the paleoshorelines outlined in Fig. 33. Vertical scale in metres.

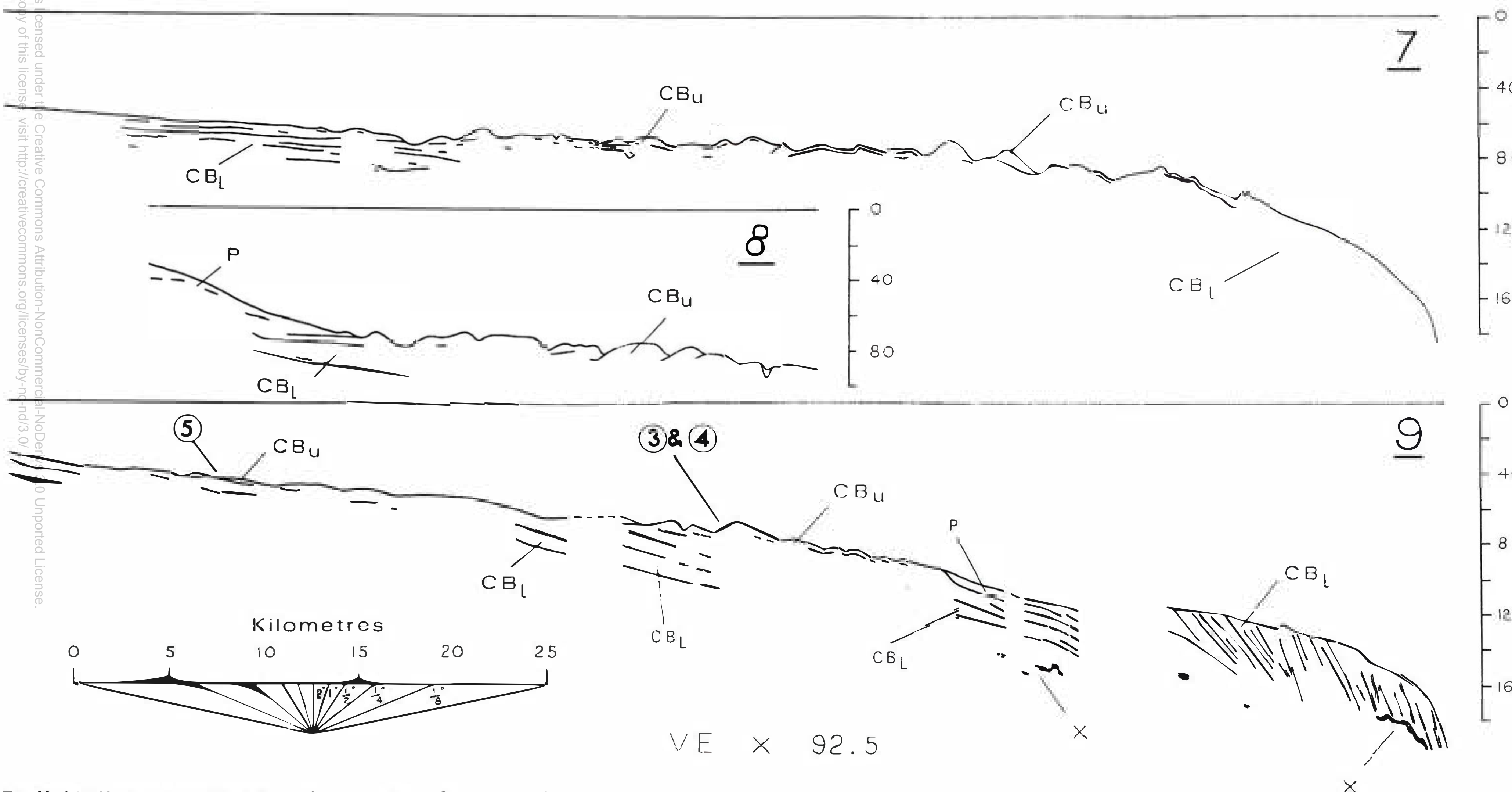


FIG. 22. 3.5 kHz seismic profiles 7, 8, and 9 across northern Canterbury Bight. P – Pegasus Bay Formation; CB_U – Canterbury Bight Formation (upper member); CB_L – Canterbury Bight Formation (lower member); X – Penultimate Glacial unit. Circled numbers indicate features associated with the paleoshorelines outlined in Fig. 33. Vertical scale in metres.

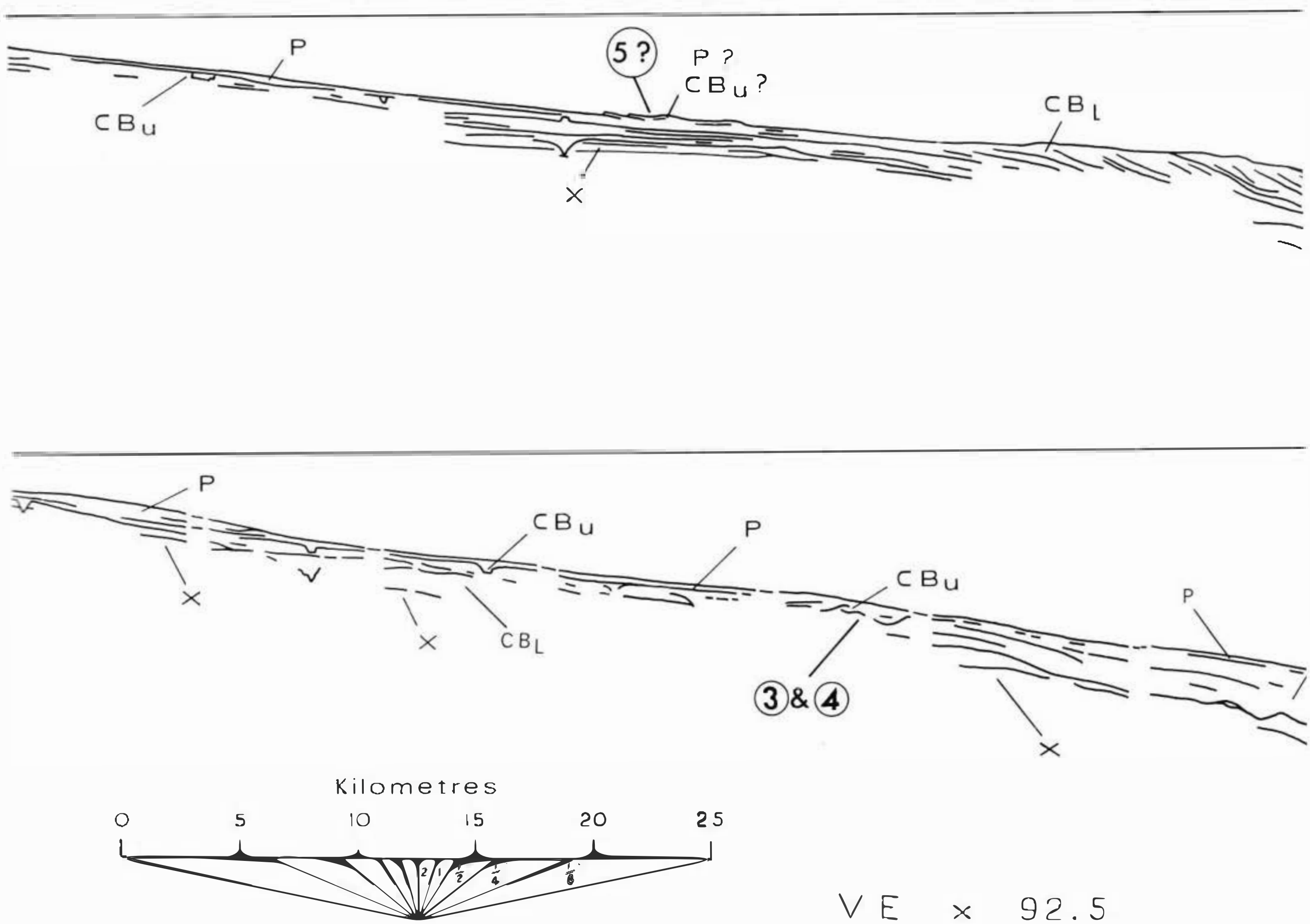
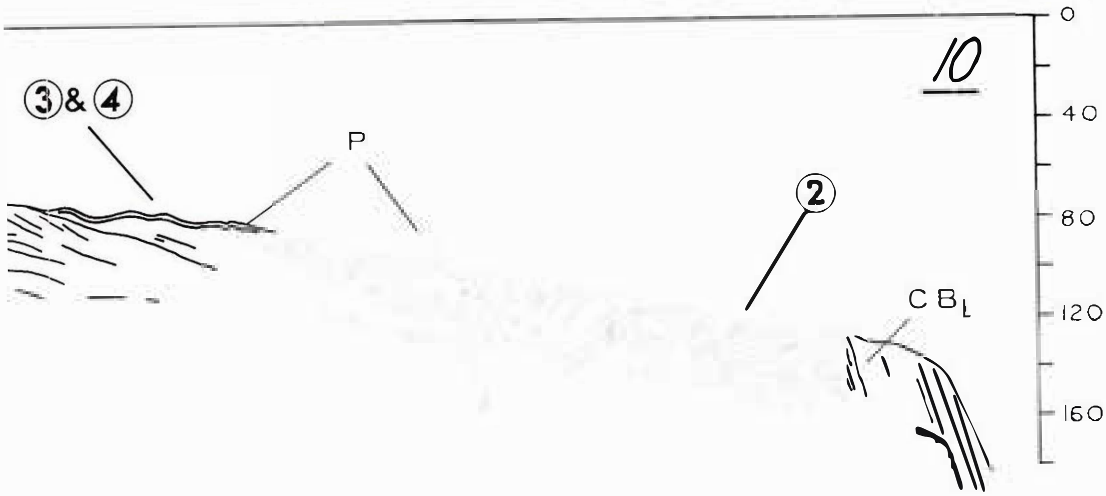
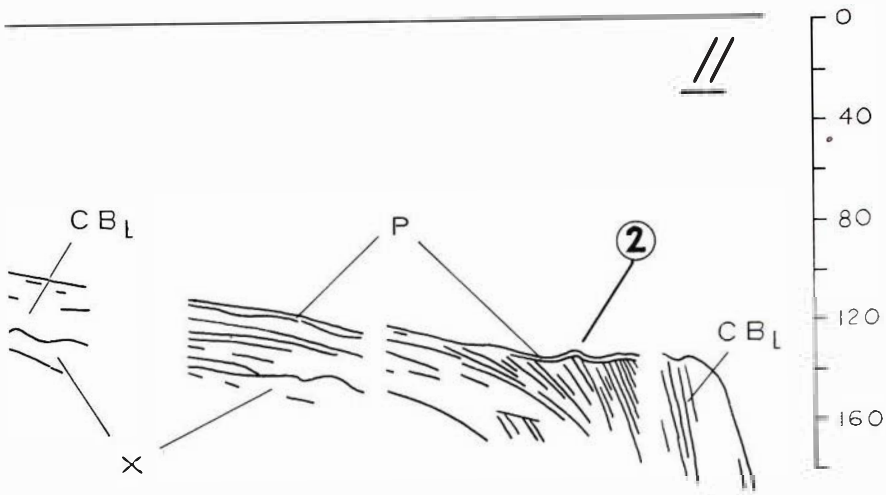


FIG. 23. 3.5 kHz seismic profiles 10 and 11 across southern Canterbury Bight. P – Pegasus Bay Formation; CB_U – Canterbury Bight Formation (upper member); CB_L – Canterbury Bight Formation (lower member); X – Penultimate Glacial unit. Circled numbers indicate features associated with paleoshorelines outlined in Fig. 33. Vertical scale in metres.



10
③&④
P
②
CB$_L$
0
40
80
120
160



11
CB$_L$
P
②
CB$_L$
X
0
40
80
120
160

Lithology and Structure

Mud and/or very fine Mode IV sand, free of gravel, form the top of the formation (*cf.* Figs 11, 12, 14).

Three cores (H435, H440, H459) in Pegasus Bay (Zone A) and one (H350) in outer Canterbury Bight (Zone E), extend into the top 3 m of the formation (*see* Fig. 9). Inner Pegasus Bay contains a muddy facies comprising heavily bioturbated sandy (Mode IV) mud and silty clay beds, 10–150 cm thick, alternating with thin beds 4–10 cm thick, of finely laminated coarse silt with few burrows (H440 and H459, Fig. 24). Outer Canterbury Bight contains a facies of muddy fine Mode IV sand and sandy mud that are so strongly bioturbated that bedding is entirely destroyed (H350). The sandy facies of the Pegasus Bay Formation, which is generally limited to those areas where the water depth is less than 25 m, is mainly composed of clean or coarsely silty, very fine, hard-packed Mode IV sand that cannot be penetrated with a piston corer. The only core from this dominantly sandy facies (H435) was obtained on the edge of the formation in outer Pegasus Bay where the sand contains enough mud to render it penetrable by piston coring. The sediment is bioturbated, muddy, very fine Mode IV sand. Shells are rare in all the cores from this formation.

The muddy parts of the formation indicate low energy conditions in which the rate of deposition is usually low enough to allow an active infauna to effectively rework the accumulating sediment. Occasional pulses of rapid sediment input are indicated by the laminated silt beds in cores H440 and H459 of inner Pegasus Bay. The sandy parts of the formation (core H435) indicate higher energy conditions.

Except along the seaward margin of the thickest deposits, where it dips gently seawards, and overlying the top of the ridge-and-swale topography of the Canterbury Bight Formation, the bedding on the seismic profiles is effectively horizontal.

Anomalies

In southern Canterbury Bight, as the Pegasus Bay Formation thins northwards, the ridge-and-swale topography of the top of the underlying Canterbury Bight Formation gradually emerges, the Pegasus Bay Formation being too thin (Profile 10, Fig. 23) to smooth the profile. The southernmost part of the ridge-and-swale Zone D (Fig. 7) therefore actually appears as Pegasus Bay Formation on the geological map (*see* p. 58). In this area the northern limit of the formation is defined by the change in surface sediment type, particularly by the sand modes (Fig. 14).

On the inner shelf in northernmost Pegasus Bay (Zone B), in the area where seismic profiles show folded rocks directly below an eroded sea bed (Profile 1, Fig. 19), the Pegasus Bay Formation thins to a veneer and is not shown separately.

The curious pinnacled terrain in the Pegasus Bay Formation shown at the outer end of Profile 1 is attributed to low angle submarine sliding (Herzer & Lewis 1979).

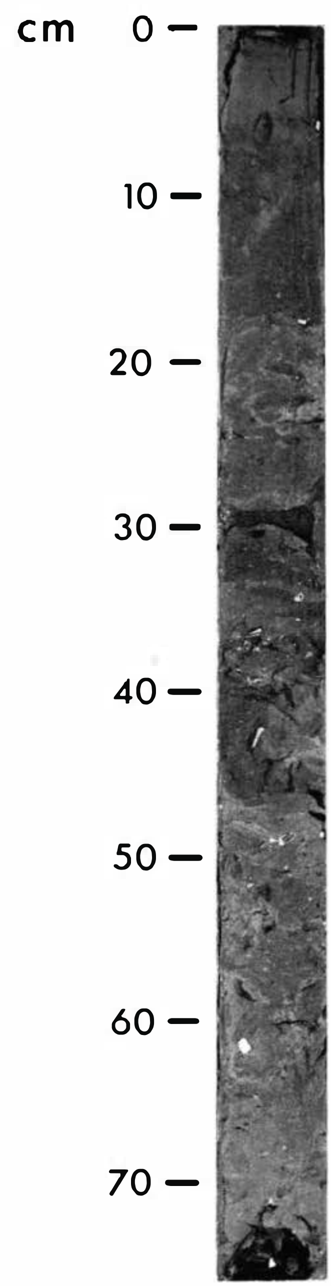


FIG. 24. Core H440 from the muddy facies of inner Pegasus Bay (Pegasus Bay Formation).

Age of the Pegasus Bay Formation

The distal part of the formation, now in relatively deep water, probably began to accumulate shortly after the beginning of the deglacial transgression some 18,000 years ago. However, because its greatest thickness is on the inner shelf, most of the formation was probably deposited within the last 6,000 years, after the sea had risen approximately to its present level (Fig. 25). The Pegasus Bay Formation is considered here to be entirely marine.

CANTERBURY BIGHT FORMATION

Type and Reference Profiles

Profile 10 (Fig. 23) (NZOI No. 1012–13) is designated as the type profile of the Canterbury Bight Formation and Profiles 6 (Fig. 21) (NZOI No. 1012–19) and 7 (Fig. 22) (NZOI No. 1012-05, 06) are designated as reference profiles.

Upper and Lower Boundaries

The Canterbury Bight Formation underlies most of the continental shelf in the study area. Its base is the top of the eroded and reworked upper part of the unnamed lower formation (X) which includes buried river channels, second-order ridges and truncated foresets (Fig. 23). On the continental slope, the boundary between the Canterbury Bight Formation and the underlying formation is evidently a paraconformity or a low amplitude disconformity that can only be identified with certainty by tracing the reflector to its distinctive equivalent on the continental shelf.

The top of the Canterbury Bight Formation shows in profiles as a diachronous sequence of truncated foresets, buried river channels and ridge-and-swale topography. About half of it is exposed on the present sea bed where it is represented by Zones C, D, and F, and about half is unconformably overlain by the Pegasus Bay Formation.

The Canterbury Bight Formation is about 35 m thick on the outer continental shelf and thins to less than 10 m near the shore. On the continental slope it thins seaward to 7 m, 50 km from the shelf edge. The formation may be divided into a lower and an upper member.

Lower Member: Lithology and Structure

The lower member, which makes up the bulk of the formation, is progradational and youngs seaward. On the inner shelf it is horizontally bedded but, as it thickens seaward, dipping foreset beds appear (e.g., Fig. 23). A low rate of sedimentation during a high sea level was thus followed by rapid sedimentation during a falling sea level.

On the continental shelf most of the lower member is buried beneath the upper member. The lower member does, however, appear to be exposed on the edge of the continental shelf off northern Cantebury Bight and on the margin of Pegasus Canyon where locally the shelf edge terrace (Zone F, Fig. 7) has cut deeply into it (Profiles 1, 3, 6, 9, Figs. 19–22). Two places where the 3.5 kHz profiler showed truncated foresets with no apparent overlying sediment were cored (H781 and H813; Fig. 9). The cores consist of compacted, very fine Mode IV muddy sand and sandy mud with a high shell content (Fig. 26; Table 5).

The upper continental slope is considered here to be the progradational front of the lower member without a significant cover of younger sediment. Two 4 m cores (H347 and H349) were taken; they consist of structureless mud with occasional silt bands and colonies of calcareous worm tubes. Rapid deposition in quiet water is inferred from the dearth of micro- and macro-fauna and from the very fine grain size. The top 20-40 cm is rich in foraminifera and sandier (Mode IV), indicating a reduction in the rate of sedimentation and a probable concomittant increase in reworking. This top layer may reflect the change to the Holocene sedimentary regime where the primary sediment source is far removed from the shelf edge. If so, it represents the Pegasus Bay Formation, but this would need to be confirmed by further work.

Very fine Mode IV sand and mud are the typical sediments of the shelf edge terrace and upper continental slope and are regarded as the typical sediments of the lower progradational member.

Upper Member: Lithology and Structure

The upper member is thin but well defined by bathymetry and sediment type. Zones C and D (Fig. 7) are its surface expression, and Mode II and III sand (Fig. 14) and Mode I gravel (Fig. 12) are exclusively its sediments. The upper member records the formation of a coastal plain and the subsequent reworking of the surface of the plain by the sea, and consists of two facies – a fluvial facies and a marine facies.

Fluvial Facies

The fluvial facies is defined by small, steep-sided, cut-and-fill features on the seismic profiles, interpreted here as buried river channels on the inner shelf (Fig. 23). At most places it is covered by the Pegasus Bay Formation and is too deeply buried to be sampled. However, it virtually reaches the sea floor in the shallow water of inner Canterbury Bight, where the arcuate shapes of the 25 m and 50 m bathymetric contours most likely represent the eroded seaward extensions of the Canterbury fan surfaces (Fig. 1). The sea bed is covered by coarse, rounded, greywacke-argillite gravels that would have been eroded from the alluvial fans.

Marine Facies

The marine facies of the upper member appears in the seismic profiles and in the bathymetry as widespread second-order ridges and as the first-order ridges and troughs that are prominent east of Banks Peninsula. Three different types of morphology corresponding to three different sediment subfacies within the marine facies were cored to a depth of 3 m:

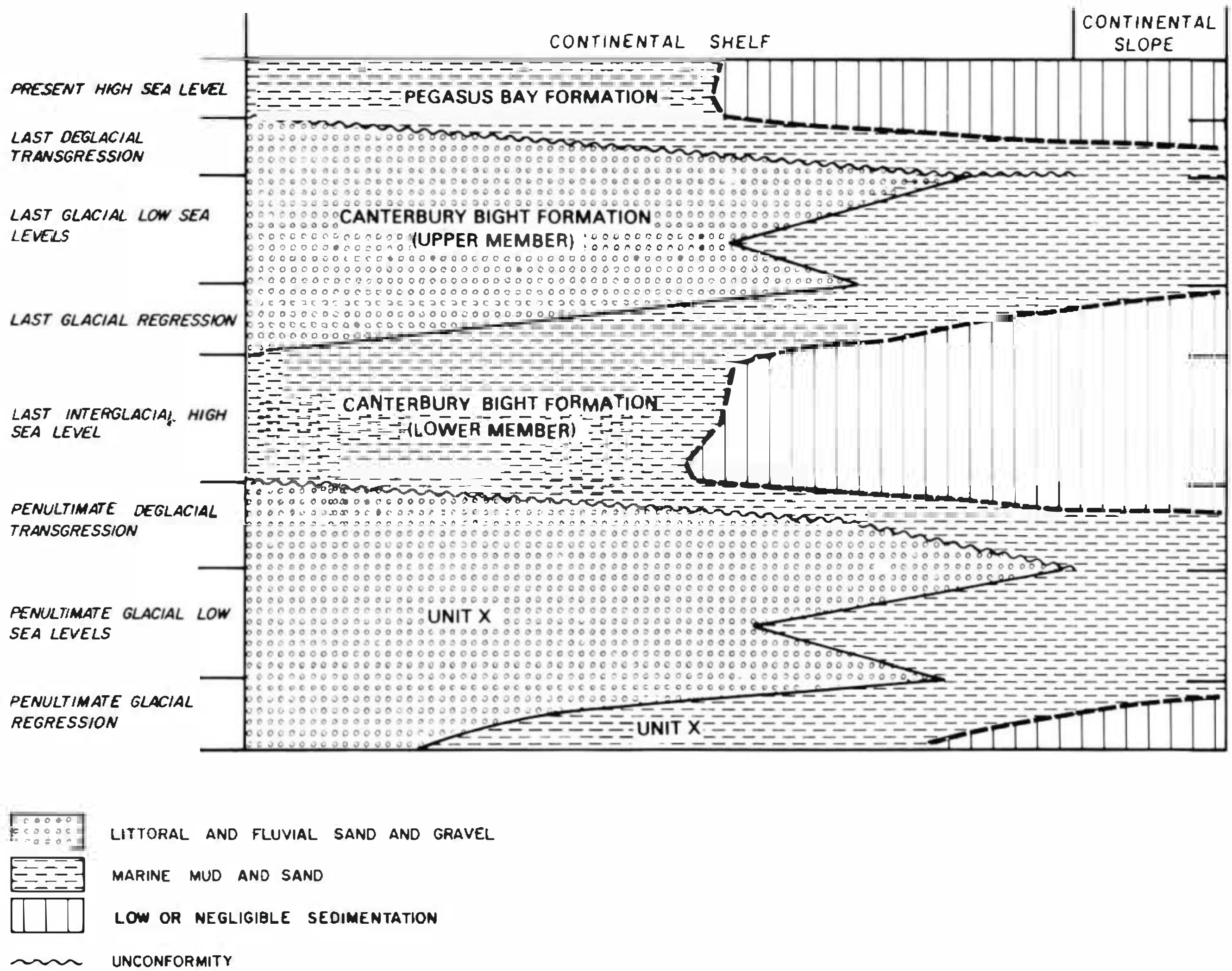


FIG. 25. Chronostratigraphic diagram of the late Pleistocene formations proposed for the Canterbury continental shelf.

(i) First- and second-order ridges.
(ii) The long troughs adjacent to first-order ridges.
(iii) The inner edge of the shelf edge terrace.

Sand modes in the cores were estimated visually as described earlier. It is assumed here that the minor mode (II) sometimes occurs with Mode III as it does in the surface samples although it cannot be distinguished visually.

(i) First- and second-order ridges

The cores taken in this facies are H353, H403, H777, H788, H789, H790, H810, and H811 (*see* Figs. 27, 28; Fig. 9 for location).

In most cases, the top 150–200 cm is composed of apparently normally graded, otherwise structureless, fine sand (Mode III) with small amounts of finely fragmented shell material. In some (H353 and H403) shells and/or pebbles are found at the top. In cores H777 (Fig. 27), H789 and H810 the structureless sand horizon is underlain by dense, cross-bedded, shell beds.

The top layers of sandy cores tend to be disturbed during the horizontal extraction of the liner from the barrel aboard ship, and the grading of the top unit may be an artefact. The top sandy unit otherwise resembles the "traction zone" of Powers & Kinsman (1953) and it probably represents sections through modern sand bodies that are moving across the shell beds of an "accumulation zone".

In core H788 (Fig. 28) there are four cyclic graded beds, each 45–75 cm thick. Each bed comprises a subhorizontally bedded sand with fine shell fragments, grading downwards to a coarsely crossbedded sedimentary breccia consisting of oblong clasts of soft sticky clay, bivalve shells (with their concave sides upwards) and sand. The structures and the inclusion of clay clasts indicate that these beds were formed during periods of very high energy that alternated with periods of

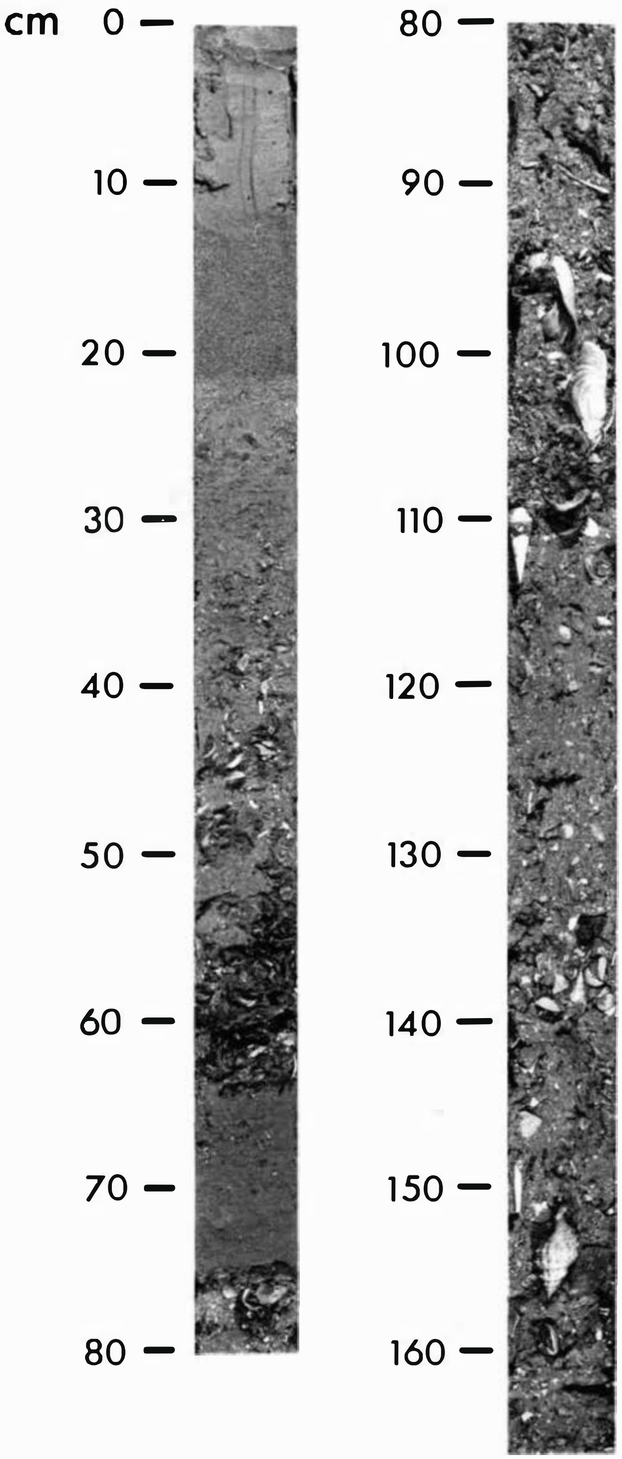


FIG. 26. Core H781 from the shelf edge terrace (lower member of the Canterbury Bight Formation).

relatively low energy leading to the deposition of thin mud layers that were later broken up.

The abundance of shells at the base of each graded bed made it possible to use radiocarbon dating to estimate the magnitude of the time interval represented between each successive bed. The commonest shells in the core are *Scalpomactra scalpellum* and *Tawera spissa*, both of which have a wide depth range (subtidal to middle shelf). The radiocarbon ages of the shell layers are shown in Table 6. The ages of the shells in the upper three beds increase downwards and are separated by 700-1300 years. However, the date for the lowest layer is younger than that for the next overlying one, implying that older and younger shell layers have sometimes been mixed during reworking, and that the cyclicity of the events may have been as frequent as 400 years (since the interval between the highest and lowest beds is about 1200 years). By comparing the present depth of the shells below sea level (59-61 m) to the sea level in the region at the time they were living (−13 to −26 m from 7340 to 9370 years B.P.; Gibb 1979) and assuming no tectonic or isostatic movement at the site, it may be inferred that they were living on the inner shelf in a water depth of approximately 35-46 m when the beds were deposited. The style of bedding and the age span of the cored interval implies that preserved here are infrequent catastrophic events, rather than a gradual accumulation. The extreme flatness of the shelf and the coarseness of the sediments preclude a rational explanation for emplacement of the graded beds by gravity flow mechanisms. Instead it would seem more reasonable to attribute the formation of these beds to phenomenal storms that occur only once in 400 years or more. Sediments that were laid down during more normal conditions here have evidently been totally destroyed and transformed into these storm deposits.

(ii) Troughs associated with first-order ridges

The troughs east of Banks Peninsula (Fig. 5 and Profiles 5, 6, Fig. 21) contain a generally muddy facies (cores H405, H778, H780, Fig. 29; Fig. 9 for location).

The top 20-80 cm of these cores consist of a normally graded mud and Mode III sand unit similar to that at the top of the cores in the first- and second-order ridge subfacies. The top unit is thought here either to have been produced during handling or to represent the modern "traction zone".

Below the top unit, two of the three cores contain alternating muddy and sandy layers, but one is entirely muddy to the bottom. The mud in these cores is moderately bioturbated, burrows being either sand or mud filled. Horizontal lamination is frequently preserved. The sand, with few exceptions, is Mode III throughout.

The muddiness of the cores indicates a low energy environment which might, in theory, be due simply to the present-day protective action of the bathymetry. If so, these muddy sediments would represent a modern infilling. However, the alternating sand layers obviously reflect occasional input from an adjacent higher energy facies. The shell bed in H405 is dominated by black, sulphide-stained *Paphies australe*, *P. subtriangulatum* and *Chione stutchburyi* (Table 5), in a matrix of coarse sand and gravel suggesting that the mud-sand alternations could well be part of a lagoonal facies. The origin of the troughs is discussed later.

(iii) Inner edge of shelf edge terrace

Except where it is mantled by Pegasus Bay Formation, the inner edge of the shelf edge terrace is the zone of change between the upper and lower members of the Canterbury Bight Formation on the surface of the outer shelf (Fig. 7). The upper member has a relatively high concentration of gravel (*cf.* Figs. 7 and 12) in Mode III sand. The lower, as mentioned above, is quite deeply eroded by the terrace and is mostly muddy Mode IV sand.

The single core taken in the terrace edge facies (H812, Fig. 30; Fig. 9 for location) penetrated 2 m into the upper member. Its top 26 cm is composed of the graded mud to sand sequence that is found in other cores. The remainder is dominated by pea-gravel in a sandy (Mode III) or muddy matrix, the muddy matrix being confined to the upppr 86 cm. The gravel contains numerous intertidal and shallow-water species (Table 5). It is thus thought here to include reworked shore deposits. The muddy matrix of the gravel in the top half was most likely emplaced by mixing of Holocene mud with the relict Pleistocene gravel through the activities of burrowing infauna.

Age of the Canterbury Bight Formation

The Canterbury Bight Formation is bounded above and below by unconformities apparently representing shelf-wide transgression surfaces, and is strongly diachronous. The lower member of the formation has been interpreted here as a marine neritic regressive sequence; the upper as a transgressed and reworked coastal plain sequence. Sedimentation of the neritic lower member upon the lower unconformity would have begun with the deglacial transgression at the close of the Penultimate Glacial, with most of the deposition occurring from the Last Interglacial high stand of sea level through the Last Glacial regression until the shelf was again exposed by the low sea levels of the Last Glacial (Fig. 25). Deposition would then have been confined largely to the continental slope.

The upper member has been well dated by radiocarbon (Table 6). Exclusively shallow-water shells, selected from cores H777, H790 and H810, range in age from 11,750 to 27,900 years B.P., while shells which can live in deeper water, selected from cores H788 and H789, range in age from 6,400 to 9,400 years B.P. The upper member is therefore considered here to have been deposited during the Last Glacial sea-level regression and sea-level low, and to have been reworked by the sea during the last deglacial transgression (Fig. 25). At places, the reworking may still be continuing.

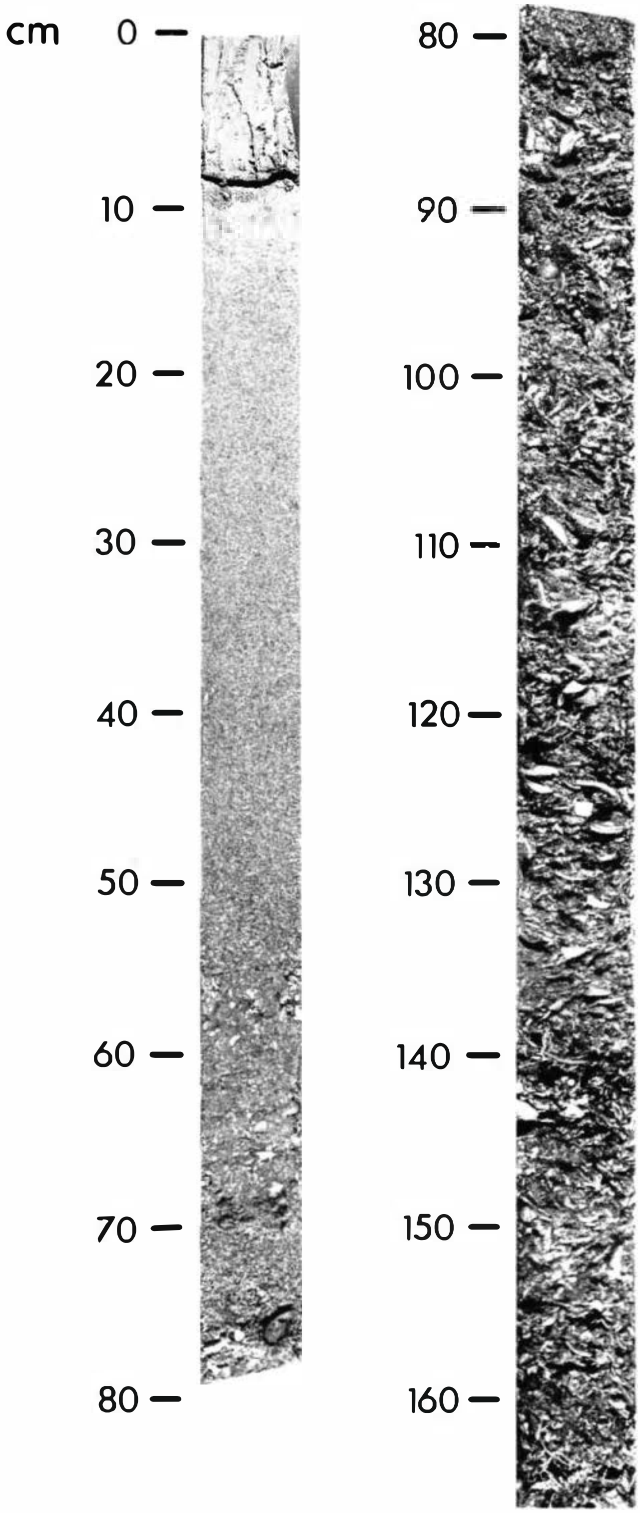


FIG. 27. Core H777 from the ridge facies of the upper member of the Canterbury Bight Formation, showing the sandy "traction zone", interpreted as part of a palimpsest sand body, overlying the shelly "accumulation zone".

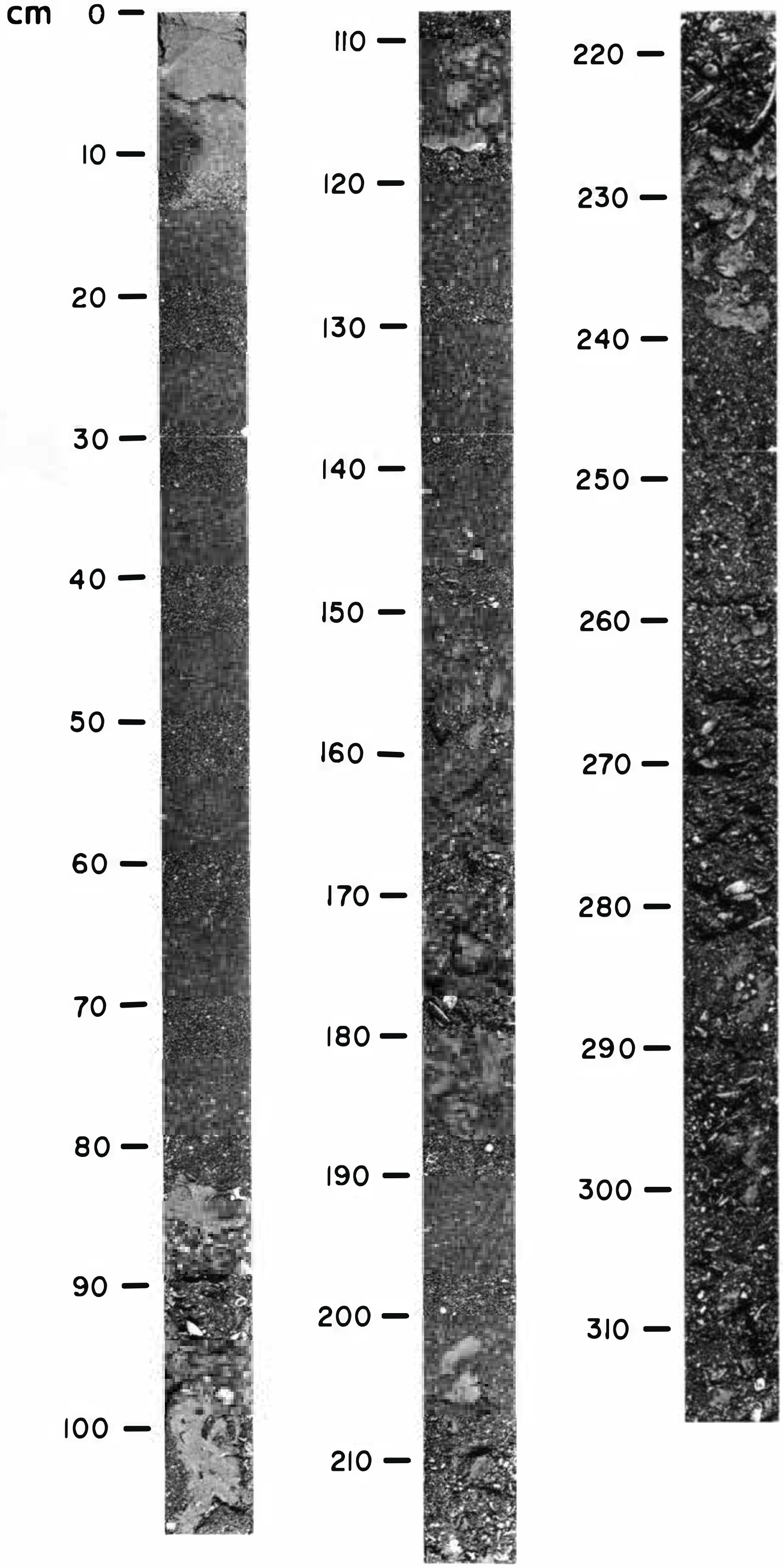


FIG. 28. Core H788 from the ridge facies of the upper member of the Canterbury Bight Formation, showing cyclic, graded beds that are interpreted as storm deposits.

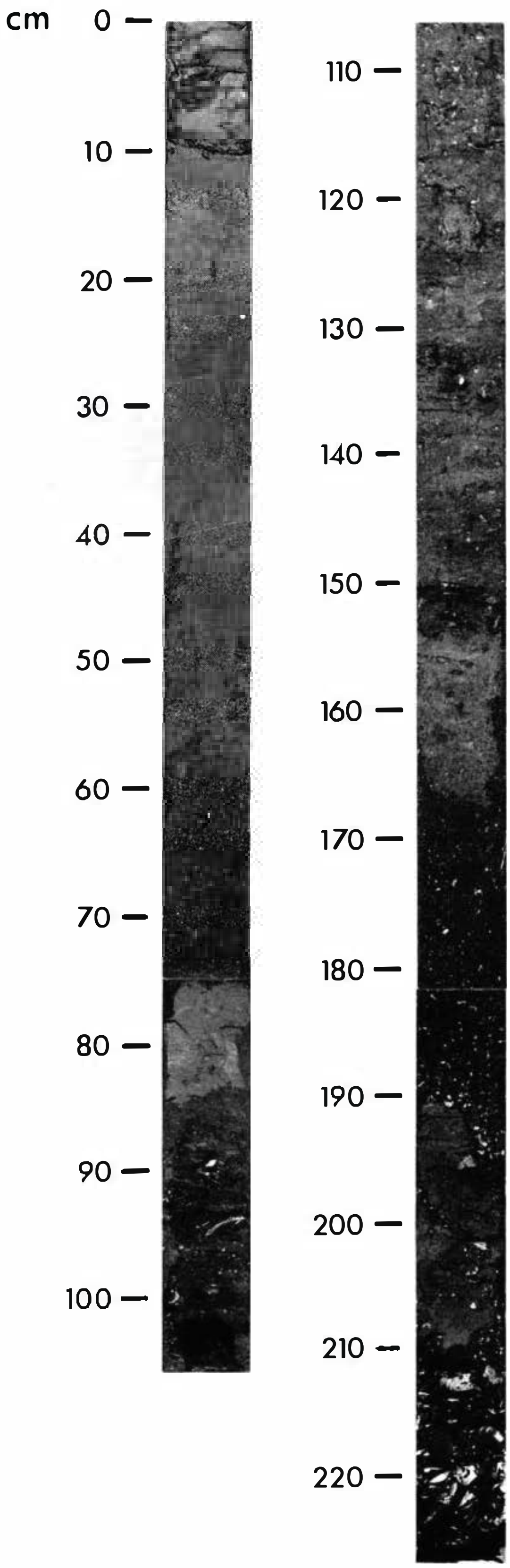


FIG. 29. Core H405 from the trough facies of the upper member of the Canterbury Bight Formation, showing alternating layers of mud and coarse to medium sand, gravel and intertidal shells.

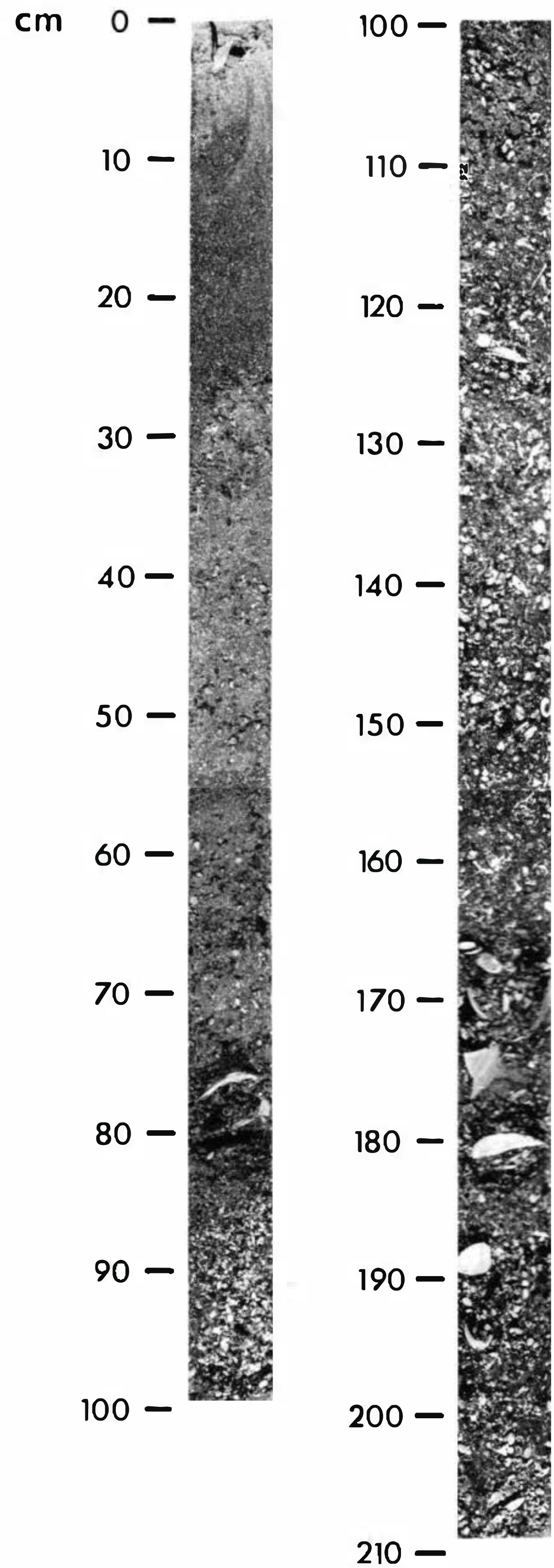


FIG. 30. Core H812 from the inner edge of the shelf edge terrace (upper member of the Canterbury Bight Formation), containing a dense deposit of pebble gravel.

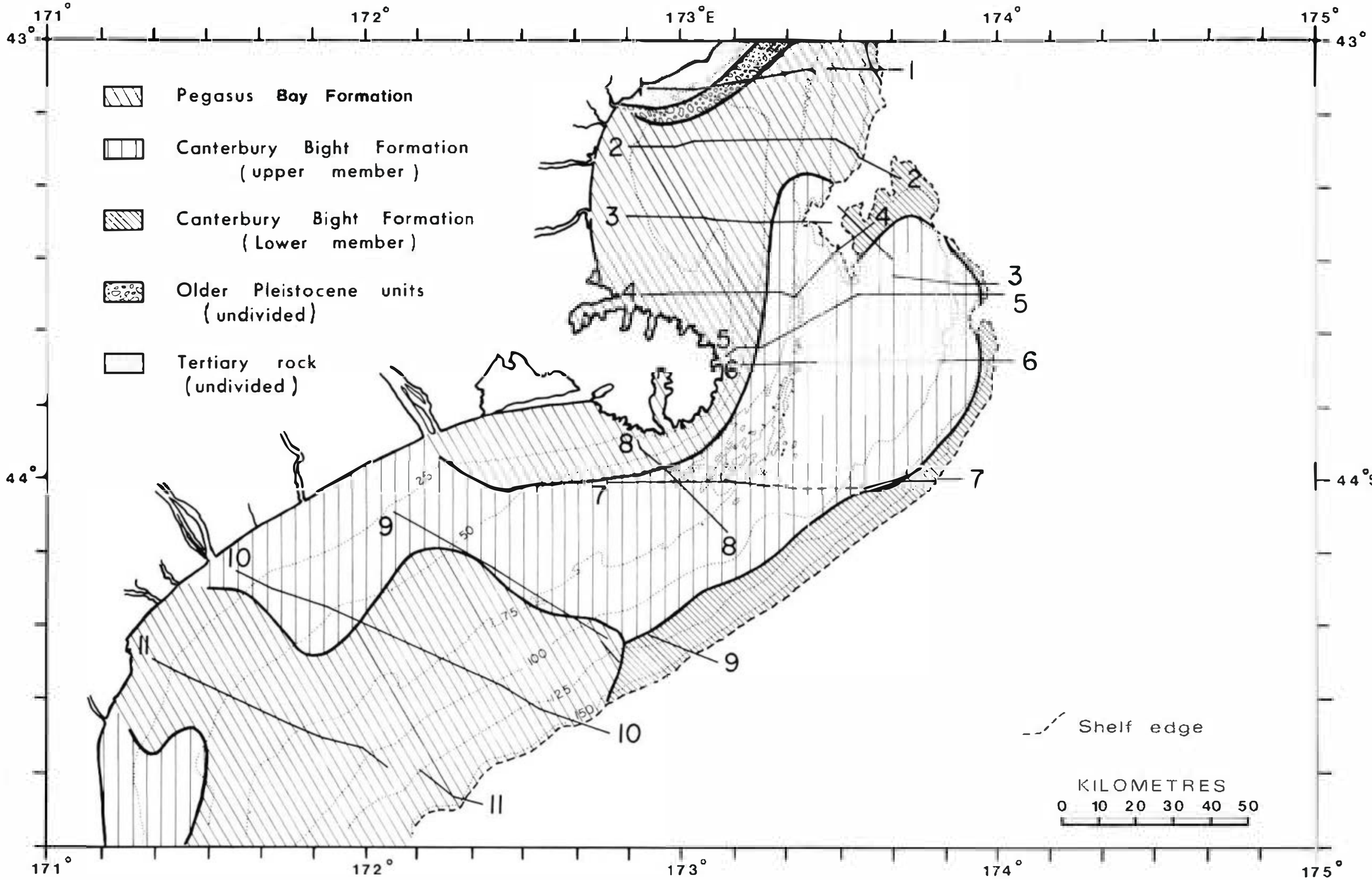


FIG. 31. Geological map of the Canterbury continental shelf. Bathymetric contours in metres.

DISCUSSION

GEOLOGIC MAP OF THE CANTERBURY SHELF

Figure 31 is a geological map of the outcrop pattern of the formations discussed above. Although the 3.5 kHz seismic profiles provide the basis for establishing the formations, the lateral formation boundaries can be more precisely defined in some areas by the boundaries between the different grain size modes, and in others by the echogram morphology and detailed bathymetry. Thus a combination of methods has been used to establish the boundaries as accurately as possible.

SEGREGATION OF SIZE MODES

The most obvious feature of the sediment distribution pattern on the Canterbury continental shelf is the virtually complete areal segregation of unimodal Mode IV sand from the polymodal assemblage of coarser sands and lithic gravel (Modes I-III, Figs 12, 14). It is generally agreed that the coarse relict sediment often found on a continental shelf was transported to its apparently anomalous location during glacially lowered sea levels and left there when the deglacial shoreline moved landward. The coastal retreat model has been proposed by Bruun (1962) and Schwartz (1965) and confirmed in field studies by Rosen (1978). During a rise of sea level on a low unconsolidated coast, erosion of the shore-face will tend to be balanced by an equal-volume accumulation on the adjacent sea floor. The shore-normal transfer that this process requires creates the thin transgressive sheet of relict materials now mantling the shelf. Input and output by longshore drift is assumed to be steady state, and river input is not taken into account. A modification of this model put forward by Dillon (1970) and Swift *et al.* (1971) explains coastal retreat and sediment redistribution due to sea-level rise on a barrier island coastline. The barrier island moves landward by a cyclic process involving storm washover of the coarse barrier sediments into the lagoon, their burial beneath the migrating barrier, and their re-emergence at the retreating shore-face.

In both the models, fine as well as coarse sediment is carried off shore during deglacial coastal retreat. Neither model embodies a satisfactory explanation for the total absence of the finer sand (Mode IV) from the relict sand/gravel sheet on the Canterbury shelf. Since all the sand modes (II through IV) that occur in the rivers of the present coastal plain must have occurred in the rivers of the Pleistocene coastal plain as well, the complete separation of Mode IV from the others is unlikely to have been achieved by river processes. Instead, it is much more likely to have been accomplished by marine processes.

It is necessary to consider the possibility that winnowing of the very fine Mode IV sand from the fine Mode III sand, which dominates the transgressive sand/gravel sheets on the shelf, has been taking place on the continental shelf for the last 6,000 years since the return to present high sea level. However, a number of obstacles present themselves:

(a) This would require stronger currents on the middle shelf sea bed than on the inner shelf sea bed. This may well be the case but remains to be proved.

(b) In several places (in northern Pegasus Bay and off Banks Peninsula) relict Mode III sand is mixed with modern mud deposits but Mode IV sand is absent. Such a gap in the energy gradient indicates that Mode IV sand was removed before the present current system was established.

(c) Mode IV sand is absent throughout the cores in the transgressive sand/gravel sheet, which contains buried shell beds 12,000–15,000 years old, dominated by littoral species that are presumed to have been deposited and reworked in very shallow water and to be undergoing no reworking now. This clearly indicates that Mode IV sand was removed (probably in shallow water) before the present current system was established.

It is therefore possible that the very fine Mode IV sand was removed from the transgressive sand/gravel sheet as it was being laid down. A useful analogy to this argument is available in the present coastal and near shore sedimentary environment.

The present coastline of Canterbury is, at different places, eroding, prograding, or stable. All three sand modes (and gravel) are at present being supplied to the coast by rivers. Off prograding or stable portions of the coast (the coast of Pegasus Bay and Kaitorete Spit) the sea bed is made up of very fine Mode IV sand (Fig. 14; *see also* Campbell 1974) and mud that is accumulating as a thick modern deposit (the Pegasus Bay Formation) on the inner shelf. The bathymetric profile of the deposit is in equilibrium with the present coastal hydraulic regime. The beaches consist of medium and fine (Modes II and III) sand and gravel (Mode I) (*cf.* Blake 1964, Campbell 1974). Such seaward fining of sediment from beach to off shore has been well documented by others (*see*, e.g., Keulegan 1948, Scott 1954, Ippen & Eagleson 1955, Ingle 1966, Johnson & Eagleson 1966, Cook 1969, Swift 1969). The sorting takes place within and just seaward of the surf zone, gravel and coarser sand being thrown landward up onto the beach while mud and finer sands are carried seaward.

Off the eroding coast — the coast of central Canterbury Bight (Kirk 1967, 1969) — the sea bed is made up of gravel and Modes II and III sand (Figs. 10, 14). Very fine Mode IV sand is apparently absent, although it may be present very close to shore in water too shallow to sample. Earlier in this memoir (p. 11) it was mentioned that the surface of the inner continental shelf off central and southern Canterbury Bight is steeper than to seaward and has the form of two very broad fans. The fans are thought here to be the eroded and submerged extensions of the Rakaia and Rangitata gravel outwash fans shown in Fig. 1. The drowned fans are well defined between the 50 m and 25 m contours, indicating that the drowning was initially rapid and that relatively little erosion took place. The later stage of coastal retreat has involved a large amount of cliffing. It is assumed here from the vestigial fluvial geomorphology and the absence of a modern fine sediment cover that the inner shelf in this area has not reached a profile of equilibrium with the hydraulic regime, that high energy conditions prevail, and that the sea bed is thus continually swept clean of fine sediment. The transport path of bedload sediment on the inner shelf in this area is northwards and shorewards (Carter & Herzer 1979). Very fine Mode IV sand introduced by the local rivers is therefore transported away towards the north-east in a near-shore belt.

During the rapid sea level transgression of the last deglaciation the profile of the sea bed off the whole coast would have been continually out of equilibrium and conditions would have been unfavourable for deposition of Mode IV sand. Any Mode IV sand in the area would thus have been removed from the transgressive sand/gravel sheet as the latter was laid down, and would have been transported northwards out of the area.

RELATIVE AGES OF THE FIRST- AND SECOND-ORDER RIDGES

Because of the complexity of the geomorphology and sediment distribution on the exposed top surface of the Canterbury Bight Formation, it is thought that some features are modern and some are old.

Theories of Origin of Ridge-and-Swale Topography

The origin of the ridge-and-swale topography on the Canterbury continental shelf is not fully understood, but much can be inferred from better known examples in other parts of the world. The best studied examples of ridge-and-swale topography are on the Atlantic continental shelf of the United States of America and in the North Sea – English Channel – Celtic Sea area of Europe. The former are on a long, linear continental shelf that directly faces the open ocean, whereas the latter are in two semi-enclosed bodies of water and the channel joining them.

Different parts of the ridge-and-swale topography on the Atlantic shelf of the U.S.A. have been explained as:

(i) Pleistocene beach ridges and barriers overstepped by the transgressing sea (Veatch & Smith 1939, Sanders 1962, Deitz 1963, Emery 1966, Garrison & McMaster 1966, Hyne & Goodell 1967, Uchupi 1970, Kraft 1971).
(ii) a drowned fluvial surface (Garrison & McMaster 1966, McKinney & Friedman 1970, McMaster & Ashraf 1973)
(iii) near-shore shoals, abandoned during deglacial coastal retreat, and subsequently modified by the inner shelf hydraulic regime (Moody 1964; Swift *et al*. 1972a, 1972b, 1973), and
(iv) modern submarine ridges formed after the deglacial transgression (Duane *et al.* 1972, Schlee & Pratt 1970).

Recent studies indicate that the sediments on the ridges and swales of the inner shelf are active at least in some areas (Duane *et al*. 1972, McKinney *et al*. 1974, Stubblefield *et al*. 1975). Wind and wave-generated currents caused by intense winter storms often disturb the entire inner shelf water column and are a very important cause of sediment movement. The currents progress parallel to the ridge axes with a helical flow pattern that scours out the troughs and carries sand obliquely up the flanks of the ridges, thus building them up. During weaker storms, sand is swept back from the crest towards the flanks. Rotary tidal currents are an equally effective cause for the present activity of some ridges (Stewart & Jordan 1965, Smith 1969).

The North Sea–English Channel–Celtic Sea region is tide dominated, although meteorologic effects are still important (*see*, e.g., Carruthers 1963; Stride 1963, 1973; Robinson 1966; Allen 1968b; Houbolt 1968; Kenyon & Stride 1970; Belderson *et al*. 1971; Bouysse *et al*. 1976). The proffered mechanism for ridge construction in this case is also one of helical flow parallel to the long axes of the ridges with scouring of the troughs and sediment transport towards the ridge crests (*see*, e.g., Houbolt 1968, Caston & Stride 1970, Caston 1972). Surface current velocities reaching 3 knots (154 cm/sec) seem to be required (Stride 1973). The constructional current is mainly tidal; degradational currents are supplied by waves which winnow the sediments from the ridge crests. Ridges in shallow water (30-40 m) are apparently active today. Ridges in deeper water (140–170 m) of the Celtic Sea are considered to have been most active during lower sea levels (Bouysse *et al*. 1976).

Second-order Ridges on the Canterbury Shelf

Ridges on the Constricted Shelf off Banks Peninsula

The second-order ridges on the constricted shelf off Banks Peninsula are numerous and high. Ridge-parallel sand ribbons and oblique-trending sand waves occur with the ridges (Fig. 15b and c; *see* Fig. 6 for location) and, like the ridges, they are thought here to be related to a three-dimensional, longitudinal flow pattern, where pairs of counter rotating, helical vortices maintain parallel strips of sand accumulation alternating with strips swept clear of mobile sands (Allen 1968a, 1968b; Houbolt 1968). Ridges are thought to form where the currents flow at > 3 knots (> 154 cm/sec) (Stride 1973), and sand ribbons where currents have maximum near-surface velocities of > 2 knots (> 103 cm/sec) (Kenyon 1970). Unidirectional surface currents higher than 2 knots and possibly as high as 3 knots have been detected in the region of constricted flow off Banks Peninsula (Herzer 1977, p. 17). The contoured bathymetry (Fig. 6) shows that the long axes of the ridges trend north to north-east, parallel to the direction of present current flow (Carter & Herzer 1979). Many ridges are visibly imbricated, the direction of imbrication indicating that they have migrated seawards (Profile 8, Fig. 22), this in turn suggesting that they are moved by the present northward-going bottom current which has a frequent wind-driven off-shore component (Carter & Herzer 1979). It is thus probable that the high second-order ridges south-east of Banks Peninsula are maintained today by the accelerated currents in the constriction caused by the peninsula (Carter & Herzer 1979).

Belderson (1964) and Stride (1973) have shown that where tidal currents flow at less than 1 knot (51 cm/sec) the depositional area for sand is flat, or in very low mounds at bedload convergences. The gradual northward disappearance of second-order ridges east of Banks Peninsula probably reflects the slackening of currents beyond the constriction. Accompanying the northward change in topography is a northward change from gravel-rich to gravel-poor sands on the sea bed (Figs 7, 12), which supports the inferred decline in current speed.

Although the ridges on the constricted shelf south-east of Banks Peninsula are thought to be active today, they may well have originated in shallower water during the deglacial sea level rise.

Ridges on the Open Shelf of Canterbury Bight

In Canterbury Bight the outer belt of second-order ridges in Zone D and the low, second-order ridges on the shelf edge terrace (Zone F) occur far to the south-west of Banks Peninsula and the zone of constricted circumpeninsular flow. Southwards the ridges become buried under a modern sandy mud deposit, indicating that these ridge-swale systems, which probably once extended south of the study area, are now inactive, dating from a time of lower sea level when the local energy conditions were higher. It is thus possible that these ridges were formed as near-shore shoals by the storm-current process described by Moody (1964) and Swift *et al*. (1972a, 1972b, 1973).

The inner band of second-order ridges in Canterbury Bight dies out about 74 km south-west of the peninsula (Fig. 7) with no evidence from seismic profiles of any buried south-westerly extension. The available data is insufficient to determine if these ridges are modern or relict.

Ridges are restricted to depths between 50 m and 150 m in Zones D and F and do not occur on the inner shelf. Near shore ridge generation is not taking place at present, active ridges apparently being confined only to the middle shelf in the region of strong currents around Banks Peninsula. Instead, modern sediments have accumulatd to a substantial depth along much of the shore and have thinly blanketed many of the ridges further off shore. It would thus appear that ridges are a widespread feature of transgressing seas, and that except for local occurrences where currents remain strong, they are superseded during periods of stable sea level by progradation of a new prism of neritic clastic sediments.

First-order Ridges on the Canterbury Shelf

First-order ridges occur in the area north-east of Banks Peninsula where the second-order ridges are largely absent. The two very long, low, broad, coast-parallel ridges, each backed by a trough on the landward side (Figs 5, 7) do not resemble any common submarine bedforms. The crests of both of these ridges were cored (H777 and H810) and in both cases dense, cross-bedded shell beds were penetrated (p. 53), the fauna consisting exclusively of species that can be found in shallow water and dominantly of species restricted to beaches and lagoons (Table 5).

There is no possibility that these first-order ridges represent tectonic features. Marine seismic reflection profiles show that there are no growing folds or faults under the ridges, in fact, rocks younger than lower Miocene are practically undeformed (Dean & Hill 1976), and the region has subsided only about 1000–1600 m since that time (a mean rate of 0.05–0.08 m/ka). The Banks Peninsula – Mernoo Saddle region is therefore, relatively speaking, very stable.

These first-order ridges, with their associated troughs, must therefore be of sedimentary origin. On the basis of their sediments, geomorphology and associated fauna, they are interpreted here as being a pair of spit/lagoon complexes that have been transgressed and reworked by the sea. Relatively minor subaerial features, such as beach ridges, dunes, etc., would have been destroyed, and submarine features such as shoals, etc., modified during the transgression, only the broad high of the barrier and the broad low of the lagoon being features large enough to withstand the reworking.

RELATIVE PLEISTOCENE SEA LEVELS IN THE STUDY AREA

The Banks Peninsula–Mernoo Saddle region, being effectively free of tectonic influence and surfaced by plausible drowned littoral features with shallow-water faunal assemblages, is a good location in which to attempt to set up a Pleistocene sea level curve for the Canterbury shelf. The curve, derived and discussed below and presented in Fig. 32, spans the period 12,000–28,000 years B.P.; for general comparison, the curves of Curray (1965) from 0–20,000 years B.P. and of Shackleton and Opdyke (1973) from 0–38,000 years B.P. are also included.

Two cores from the Banks Peninsula–Mernoo Saddle region, and one from about 35 km south of the peninsula, contained enough shallow-water shells to allow dating of one or two selected very shallow-water species.

Shells of *Paphies australe* and *P. subtriangulatum*, obtained in one core from the crest of each first-order ridge, have the following radiocarbon ages (Table 6): those on the outer ridge (H777) are 27,900 ± 1,550 years old between 1.22 and 1.67 m below the surface, and 24,500 ± 1,000 years old between 0.8 and 1.22 m; those on the inner ridge (H810) are 15,100 ± 200 years old 0.95–1.42 m below the surface. The depth ranges of these two dated species are strictly intertidal (the maximum tidal range in New Zealand being 3 m), and where these shells have been used the sea-level curve (dotted line, Fig. 32) is very precise.

Shells of *Zethalia zelandica* obtained in the core south of Banks Peninsula (H790) are 11,750 ± 250 years old between 1.7 and 2.07 m below the surface. The dated species in this third core has a rather wider depth range of 0–20 m; the sea-level curve could pass through the depth at which these shells plot or up to 20 m above it. Here, it is arbitrarily drawn 10 m above their plotted depth, midway through their depth range.

The lowest sea level on the new curve presented here was measured from the nick point of the shelf-edge terrace (the deepest detected shoreline on the shelf) and, in the absence of radiometric age control, is arbitrarily drawn at 18,000–20,000 years B.P.

On the portion of the curve younger than 20,000 years B.P., the data points (H790 and H810) agree well with the published Late Pleistocene sea-level trend of Curray (1965) and less well with that of Shackleton and Opdyke (1973). However, some consistent disagreement is expected since the curves were derived by different methods, the Curray curve being derived from radiocarbon-dated material on the North American

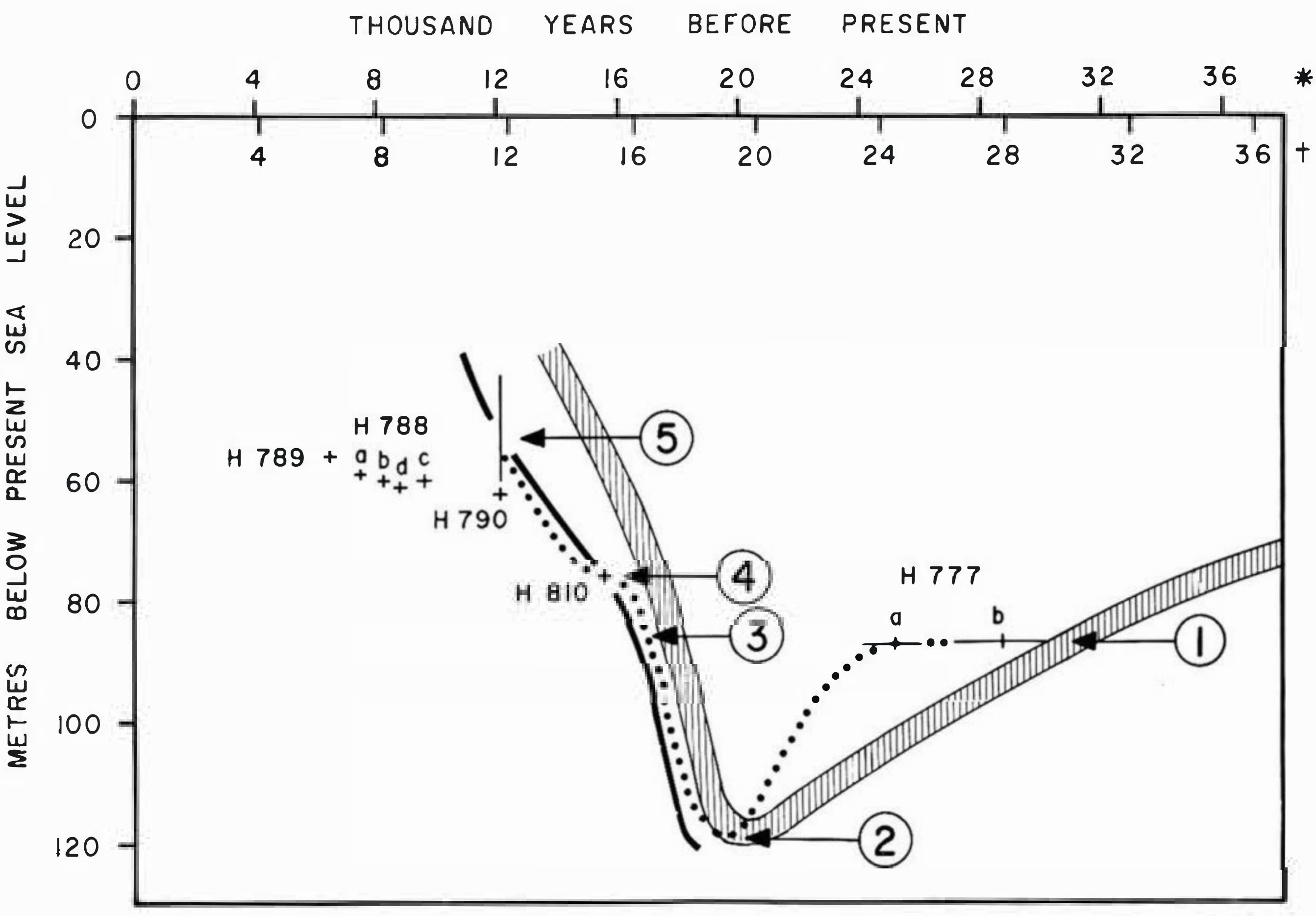


FIG. 32. Radiocarbon ages and depth below present sea level of dated species from shell layers under the Canterbury continental shelf. The magnitude of ^{14}C dating error is shown for each sample by the length of the horizontal bar. The solid line is the mean sea level curve of Curray (1965) from 0 – 20 000 yr B.P.; the vertically hatched zone shows part of the sea-level trend proposed by Shackleton and Opdyke (1973); the dotted line is the sea-level curve proposed here for the Canterbury shelf in the vicinity of Banks Peninsula. Circled numbers 1 – 5 indicate sea-levels corresponding to shoreline positions shown in Figs 19–23 and 33.
* age using 5730 yr ^{14}C half life (Godwin 1962)
† age using 5568 ^{14}C half life (Libby 1955)

continental shelf and the Shackleton and Opdyke curve from paleotemperatures and ice volumes inferred from ^{18}O isotope ratios of foraminifera in deep-sea cores. The trends are nevertheless all reasonably parallel.

On the portion of the curve older than 20,000 years B.P. the data points (H777a and H777b) support the evidence of Morner (1971) and Shackleton and Opdyke (1973) that a cool climate and intermediate low sea level prevailed prior to the Last Glacial maximum. However, the curve diverges significantly from that of Shackleton and Opdyke (1973); where their curve records a continuously falling sea level, the new curve presented here records a long stillstand from about 29,000 to 25,000 years B.P. Although it could be argued that the positions of H777a and b to the left of the Shackleton and Opdyke curve might be due to contamination of sample site H777 with young *Paphies* shells when littoral conditions returned during the deglacial transgression, this would need to be proved by individually dating a number of single shells from the location to see if two populations of different age were in fact present; until this is done the ages of H777a and b must be accepted as valid and with them the occurrence of at least 4,000 years of stillstand during that period. Good data on the positions of sea level prior to 20,000 years B.P. are still rare and the validity of this stillstand is strongly corroborated in this case by the interpreted paleogeomorphology of the outer first-order ridge as a major spit; well developed shoreline features of this magnitude would be expected to have formed during such a significant period of relative sea-level stability.

The outer first-order ridge is proposed therefore as the shore of the last interstadial stillstand which preceded the main Last Glacial ice advance. The lower formation (X) is then proposed to be of Penultimate Glacial age, and disconformities related to minor regressions and transgressions during the Last Glacial would thus be hidden in the Canterbury Bight Formation.

The inner first-order ridge, interpreted on similar geomorphological and faunal grounds as also being a spit, would have similarly required a stillstand of sea level for its formation. Sample H810 with a dominantly intertidal and shallow-water fauna dates this stillstand at around 15,000 years B.P. during the deglacial transgression. An inflection has been put into the curve at this point to show this.

HISTORY OF THE REGRESSIVE-TRANSGRESSIVE SURFACE

With the ancient and modern ridges distinguished, and a local relative sea-level curve established, a chronological sequence of Late Pleistocene-Holocene events on the shelf can be worked out. In the region of Pegasus Canyon, the terrace truncates the end of the broad, low, eastern branch of the outer first-order ridge that passes east of the canyon head (*cf.* Figs 5, 7). The ridge has been interpreted above as the remains of an old shore zone. It is inferred therefore that during the interstadial that gave rise to the shore dated here at 24,500–27,900 years B.P., the shoreline stood just east of the head of Pegasus Canyon (shoreline position 1, Fig. 33–1). A large spit/lagoon complex formed, the lagoon opening northwards into the canyon. Although the interstadial lagoon has subsequently been largely infilled and locally buried, the original position of the lagoon and spit are recognisable on Profiles 5 and 6 (Fig. 21) by deep cut-and-fill structures midway across the shelf, flanked on the east by a broad low ridge. The positions are denoted by a circled 1 on the profiles. Off Canterbury Bight there is no evidence in the profiles (Profiles 9, 10 and 11, Figs. 22, 23) for a barrier/lagoon system. Instead, with a relatively stable sea level, a thick, prograding wedge of sediment, analagous to the present-day one in northern Canterbury Bight, developed and the shore migrated very slowly seawards.

Straightforward progradation took place in Canterbury Bight because this region was at the advancing foot of the Canterbury Plains with its copious direct input of glacio-fluvial sediment. A spit/lagoon system formed east of present day Banks Peninsula because this latter region was then, from a fluvial aspect, in the depositional shadow of the mountains which now form the peninsula. Furthermore, sediment from the Waimakariri and Ashley Rivers would have been longshore-drifted northwards, and therefore would have contributed little to the area east of these mountains. Sediment input would have been almost exclusively by longshore and shelf transport from the south, and any long continued period of sea level stability would have led to the development of a spit. The spit extended well north of the depositional shadow of the mountains because Pegasus Canyon would have prevented the eastward progradation of the northern part of the plains.

As shown above (p. 59), coastal stability or progradation leads to the accumulation off shore of very fine Mode IV sand and mud and the accumulation on shore of the coarser Mode II and III sands and gravel. The progradational portion of the Canterbury Bight Formation at this time would thus have been forming from Mode IV sand and mud while the surface of the shoreline and spit would have been forming from gravel and Mode II and III sands. Gravel and sand, carried northwards by littoral drift and currents on the inner shelf, would have poured into Pegasus Canyon through the small tributaries that enter it partway along its length.

After the inferred interstadial, the sea level fell quickly (*see* Fig. 32). A continued high rate of terrigenous sediment input during this fall is implied by the persistence of a thick foreset sequence right to the shelf edge (Profiles 9, 10, 11, Figs 22, 23).

When the sea stabilised at its lowest level during the last glacial maximum 18,000–20,000 years ago, it cut a bench in the newly deposited unconsolidated sediments of the shelf edge while progradation continued on the upper continental slope. The landward margin of the shelf edge terrace thus formed (Figs 5, 7) represents shoreline position 2 (Fig. 33–2 and cross-sections Figs. 19–23). Along the south-east-facing portion of the terrace in the southern half of the study area, southerly storm conditions were favourable for the generation of second-order ridges (Figs 7, 33 – 2, and Profiles 10 and 11, Fig. 23). In the north, the terrace surface remained smooth (Profile 3, Fig. 20).

Coarse sediments accumulating on beaches at this time are now distributed in the large belt of gravel that lies adjacent to the terrace (Fig. 12). Very fine Mode IV sand and mud were carried both seawards on to the continental slope and northwards along the narrow shelf towards Pukaki and Okains Submarine Canyons. The coarse beach sediments would also have been transported northwards into the submarine canyons by the dominant southerly swell. The loss is assumed to have been balanced by the input of the longshore-drifted gravel and sand from the south.

With the onset of deglaciation, much of the terrace was evidently drowned without much modification, suggesting that the sea level rise was initially fast. It is assumed here that the terrace once extended through Mernoo Saddle but was destroyed during the earlier part of the deglacial rise of sea level by constricted, high-velocity currents and swell. The latter may have been focussed on to this part of the shelf by the convex isobaths.

During the deglacial sea level rise, the coastal regime was one of erosion and retreat. As shown earlier (p. 59), coastal retreat leads to the off-shore transfer and accumulation of the coarse on-shore sand and gravel, and the removal of mud and very fine Mode IV sand from the shelf system. Sediments eroded from the coastal plain, which probably consisted mainly of a beach-ridge and dune terrain, were redistributed on the continental shelf. Gravel and Modes II and III sand would have formed a shelf transgressive sheet. Mud and Mode IV sand would have briefly entered the transgressing littoral system and have been transported northwards away from the nonequilibrium sea bed and into the submarine canyons. As the retreating beach migrated westwards, gravel and sand carried north in the littoral drift would have poured into Pegasus Canyon at successive points along its length. The shoreline and sea bed configurations during the sea level retreat phase are discussed below.

When the rising sea had transgressed a short distance across the shelf, it encountered the great high of the old interstadial shore complex (outer first-order ridge) (Fig. 7). As the sea overstepped, the surface of the ridge would have been drastically reworked (Fig. 33–3). This event, marked by shoreline position 3, would have taken place, according to the curve, 17,000 years ago.

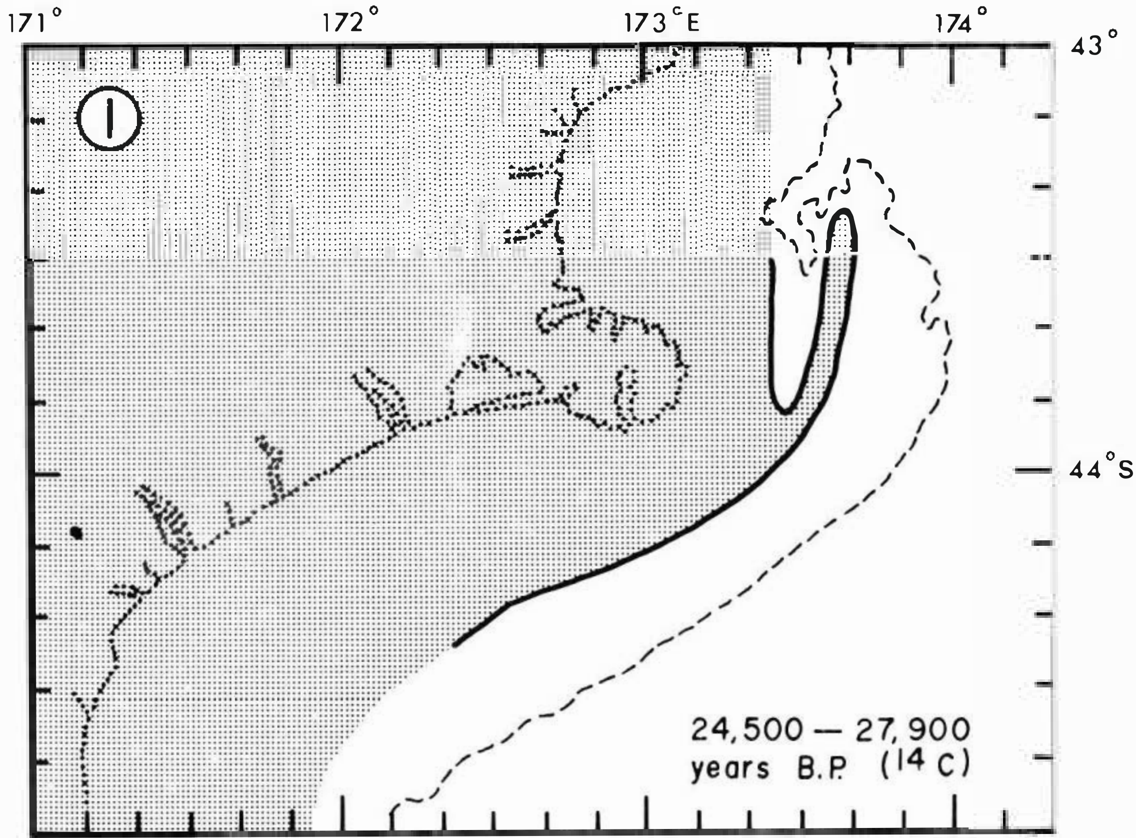
In Canterbury Bight, the sea bed appears to have been worked into low shoals probably by large waves and storm currents, generated mainly from the south (*see* p. 61). These shoals are now represented by the present second-order ridges of outer Zone D in Canterbury Bight (Fig. 7; Profiles 9, 10, 11, Figs 22, 23).

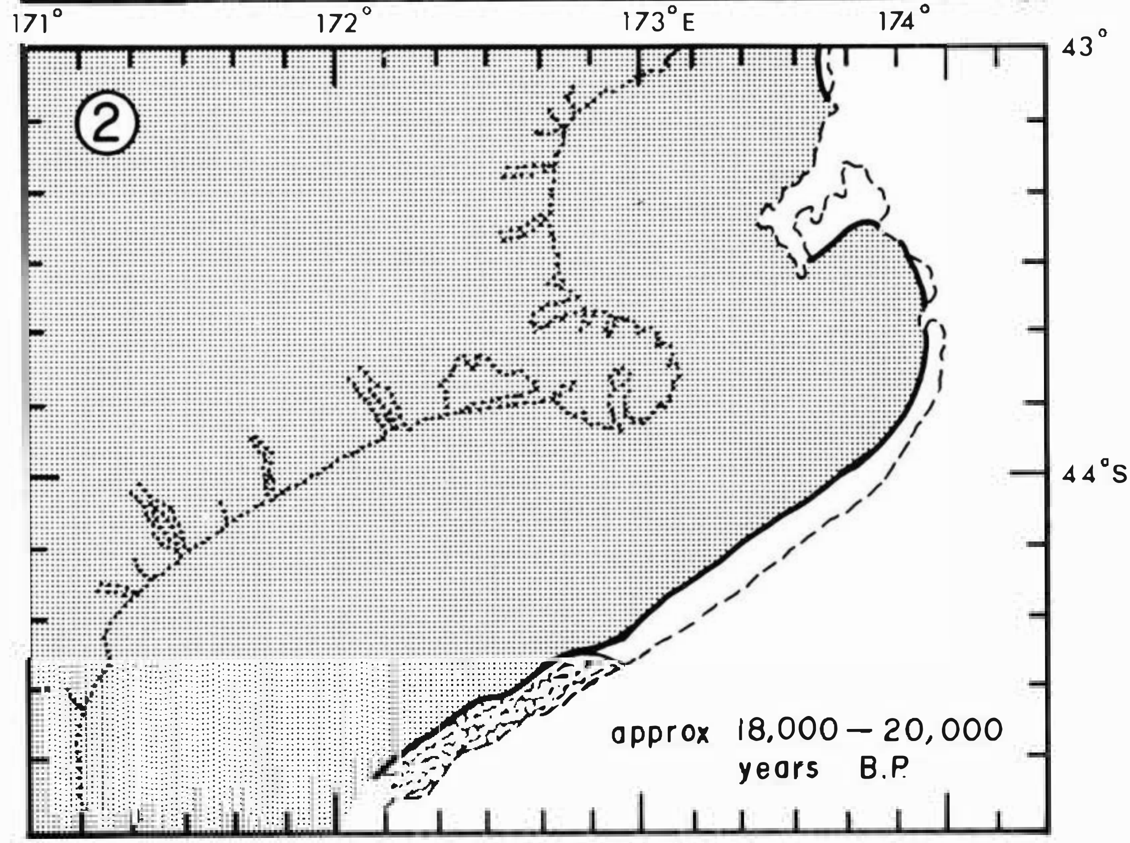
South-east of Banks Peninsula, reworking was probably so intense, because of the constricted and accelerated tidal and storm currents, that any pre-existing interstadial ridge was completely destroyed and remoulded into high second-order ridges (Profiles 7, 8, Fig. 22). Obliteration of the shelf edge terrace probably continued, at least up to the time of shoreline 3.

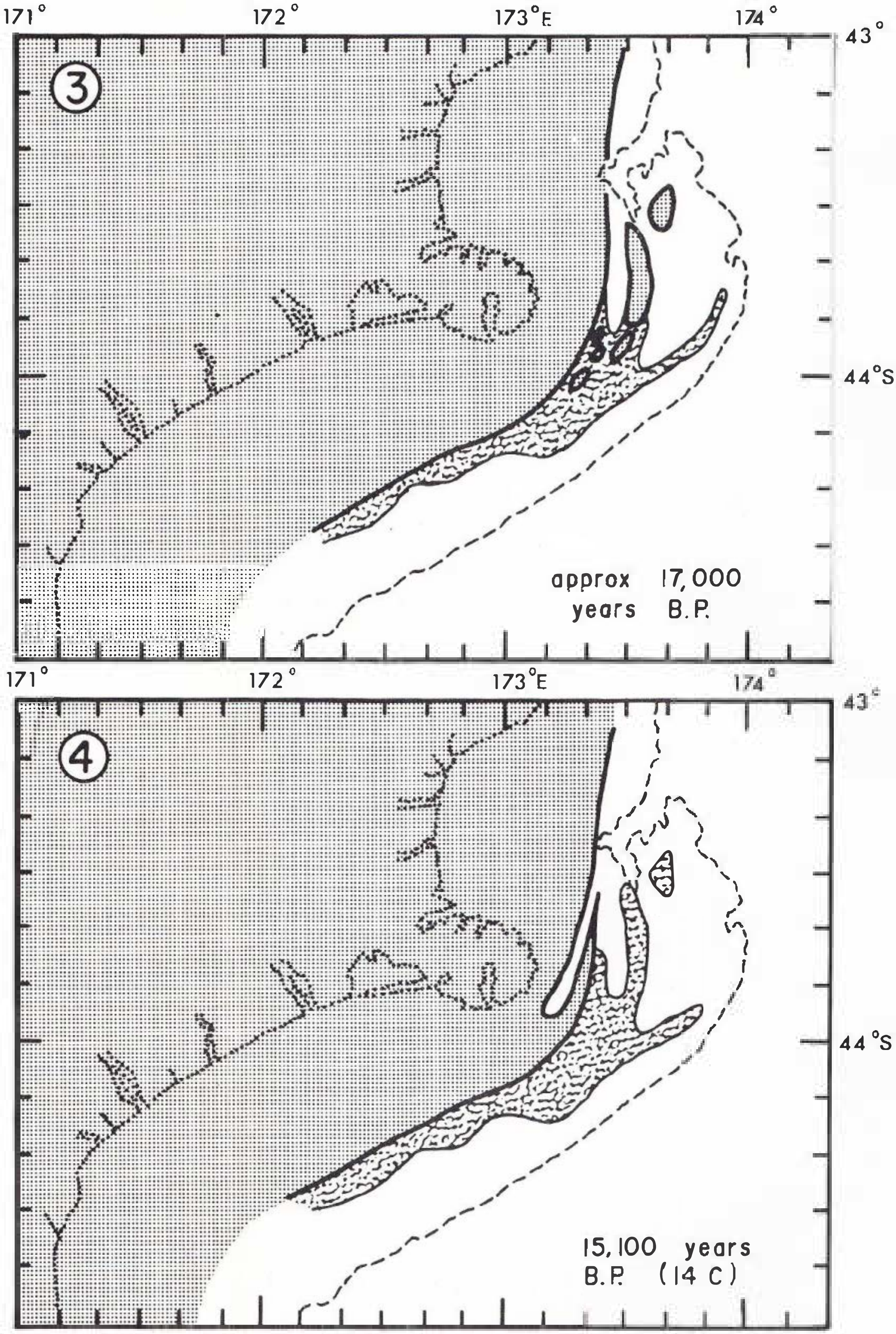
North-east of Banks Peninsula, where the off-shore tidal and storm currents would have been reduced relative to the area further south, reworking evidently resulted merely in the formation of a transgressive gravel and sand sheet without shoal formation. As a consequence, the bathymetry in this area has not been diversified by second-order ridges (Figs 5, 7), and stages in the overstepping of the interstadial spit can thus be deciphered on the basis of the existing morphology.

The argument runs as follows. The outer first-order ridge is forked near the head of Pegasus Canyon (*see* p. 14). The western fork is interpreted here as a post-glacial modification of the earlier-formed interstadial spit which extended up the eastern side of the canyon. When the shore of the rising sea reached the vicinity of the old spit (the present eastern limb of the outer first-order ridge) there would have been a temporary return to the last interstadial situation of a spit backed by an extensive lagoon (Fig. 33–1). The lagoon opened northward into Pegasus Canyon. As sea level neared the crest of the spit, the spit would have occasionally been overtopped by storm washover. A permanent breach would have developed near the head of the submarine canyon, where washover sediment, carried across the spit, would have spilled into the canyon and been lost to the spit system. With the re-entry of the canyon head into the littoral system, the crest of the spit would have quickly shifted westwards, to a position west of the new sediment sink formed by the canyon head (Fig. 33–3); the spit segment north of the breach would thus have been abandoned, although remaining as an off-shore shoal. The detailed bathymetry (Fig. 5) is consistent with the postulated breach and new spit alignment and there is some evidence in the bathymetry

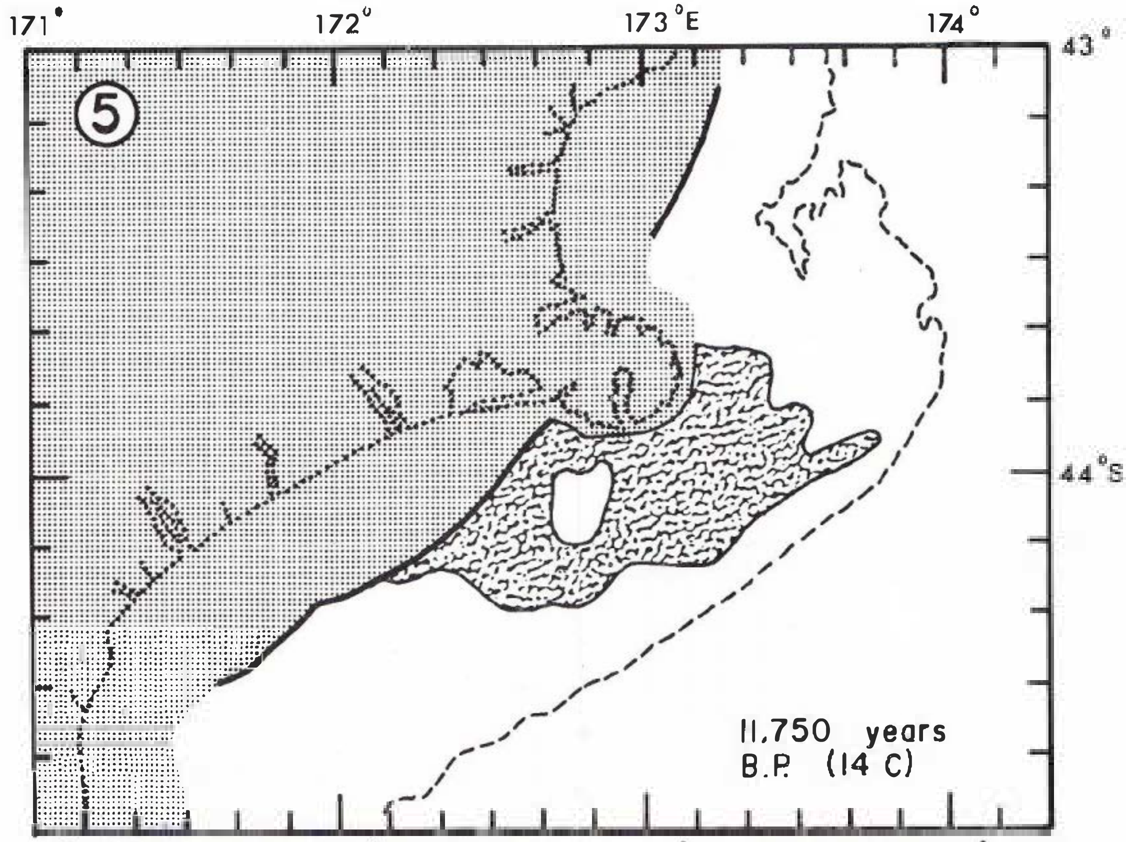
FIG. 33 *(opposite).* Positions of successive Late Quaternary shorelines (heavy lines) on the Canterbury shelf. Shoreline ages that are based on radiocarbon-dated shells are indicated by ^{14}C. Other shoreline ages are inferred from the sea-level curve for the area (Fig. 32). Land areas are shaded. Areas of inferred active off-shore shoals or submarine ridges are indicated by a hash pattern. *See* Figs 19–23 for positions of shorelines on profiles.

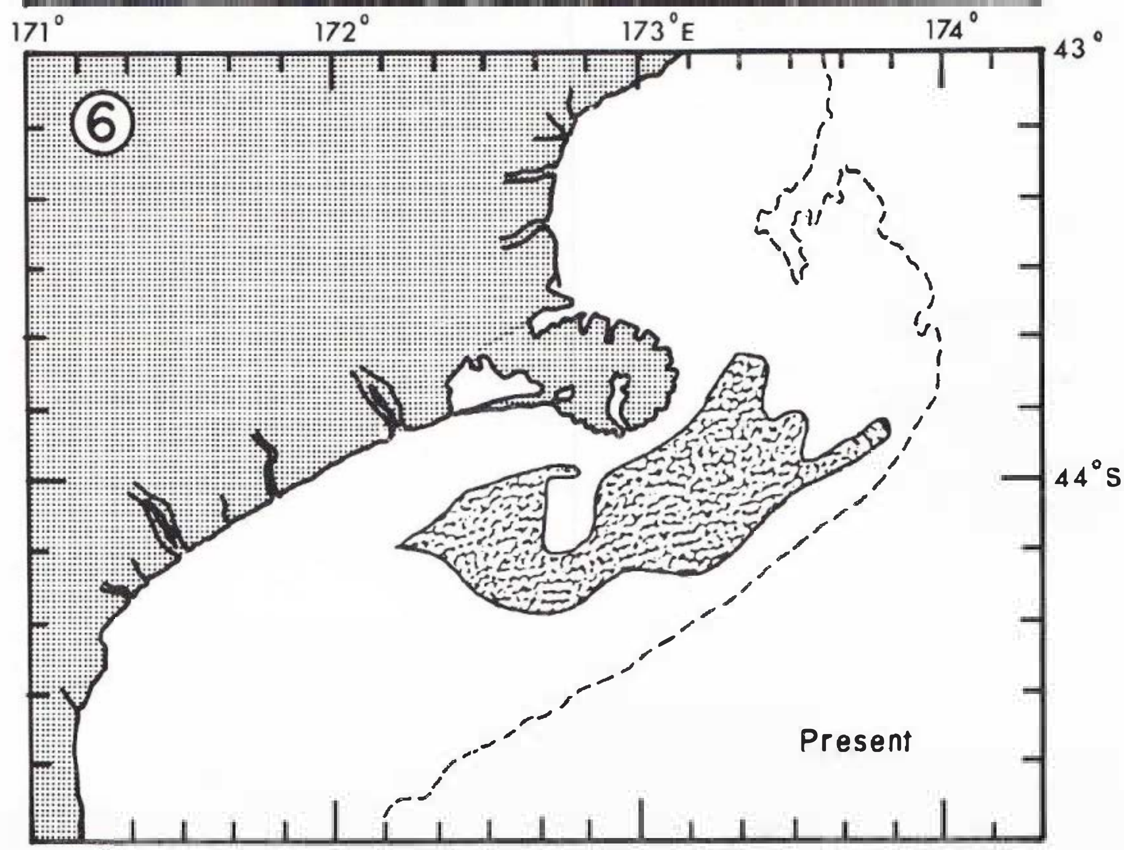

171°
172°
173°E
174°
43°
44°S
1
24,500 — 27,900
years B.P. (14 C)


171°
172°
173°E
174°
43°
44°S
2
approx 18,000 — 20,000
years B.P.



171°
172°
173°E
174°
43°
44°S
3
approx 17,000 years B.P.
4
15,100 years B.P. (14 C)


171°
172°
173°E
174°
43°
44°S
5
11,750 years
B.P. (14 C)


171°
172°
173°E
174°
43°
44°S
6
Present

that the southern end of the spit was breached as well. The extensive infilling of the northern part of the lagoon that took place during the shift of the spit is evident in Profile 5 (Fig. 21) where the muddy lagoonal facies reflectors are seen to be rather deeply buried. The old interstadial lagoon and spit positions are denoted by a circled 1. On the profile, the new spit crest appears just to the east of the lagoon and west of the old interstadial spit. The new lagoon and spit positions are denoted by a circled 3 on the profile. A short distance to the south (Profile 6, Fig. 21), where the spit crest did not migrate appreciably, as shown by the relative positions of 1 and 3 on the figure, the muddy lagoonal facies is still at the surface (*see* p. 54), only slight infilling (from the east) being apparent.

A further 10 m rise of sea level to about the present 76 m isobath (Fig. 5) was followed by a stillstand and the formation of the inner first-order ridge – shoreline position 4 (Figs 5, 33-4; Profiles 5, 6, Fig. 21). It is assumed here to have been a spit/lagoon complex similar to the outer one and according to radiocarbon dating it formed 15,100 years ago.

During the formation of this spit, conditions would have been considerably different from those of the present day (Fig. 33-4). To the east, the drowned interstadial spit (outer first-order ridge), only 10 m deep, would have damped the ocean swell. To the south-west there was probably a shallow system of active shoals (second-order ridges) which would have reduced the swell from that quarter. The northward longshore drift may therefore have been much reduced and even at times replaced by southward drift because the only deep open water lay to the north-east through Pegasus Canyon.

South and south-east of Banks Peninsula no barrier/lagoon system formed during the stillstand. Instead, reworking of the shallow sea bed into second-order ridges probably continued off the cape that would have existed south-east of present-day Banks Peninsula. Further south, off Canterbury Bight, where the shelf beyond the 75 m isobath slopes more steeply than it does to the north, the shore would have still been in the outer part of Zone D near the old interstadial shore line and near-shore, storm-dominated shoals probably remained active.

Shortly after the renewed rise of sea level from the 15,100-year shore, the supply of littoral gravel to Pegasus Canyon would have ended.

Subsequent events of the deglacial transgression are less clear. A radiocarbon age of 11,750 years B.P. was obtained from 0–20 m depth-range shells at a depth of 63 m in Canterbury Bight (H790, Table 6). Assuming that the animals (*Zethalia zelandica*) were living within 20 m of sea level, a very approximate shoreline position for that time is drawn on the surface of the Canterbury Bight Formation along the 50 m isobath (shoreline position 5, Fig. 33–5). Core H790 was taken 30 km east of this line among ridges and swales that would have been part of a broad off-shore system of active shoals or submarine ridges at the time.

Second-order ridges are assumed here to have been active south-east of Banks Peninsula during this phase, since they are inferred to be so today (*see* pp. 60-61). Banks Peninsula was already a prominent headland by this time, preventing the northward movement of gravel into Pegasus Bay. The inner belt of second-order ridges south-west of the peninsula may have been forming at this time.

In Canterbury Bight, the arcuate shapes of the drowned Rakaia and Rangitata fans are visible. Their good preservation implies that there was no stillstand within their bathymetric range. Evidence from Foveaux Strait (Cullen 1967) supports a very rapid sea level rise during this phase, beginning about 11,000 years ago and ending about 9,300 years ago.

Subsequent shore retreat in central Canterbury Bight was by cliffing (Fig. 17). It is assumed that the greywacke gravel now exposed on the sea bed of inner central Canterbury Bight is that part of the eroded fans which was not moved northward along the submerging coast.

The final phase of sea level rise (10,000 years B.P. to present) along the Canterbury coast has been described by others (Jobberns 1926, 1927; Speight 1930, 1950; Blake 1964; Suggate 1968; Kirk 1969; Armon 1970, 1974; Gibb, 1979).

SHELF SEDIMENTATION DURING THE LAST 6,000 YEARS

During the last 6,000 years sea level has stabilised near its present level. In some places on the continental shelf, modern sediment has accumulated; in others, exposed relict sediments remain exposed, but have adjusted to the modern shelf hydraulic regime.

Dispersal of Modern Input Sediment

Sediment that has been added to the continental shelf system during the last 6,000 years is considered here to be forming deposits in equilibrium with the present hydraulic regime. They consist of very fine Mode IV sand and mud and constitute the Pegasus Bay Formation.

A shelf-wide blanket of sediment derived from the rivers south of the study area and identified as modern by its fauna and grain size modes (Mode IV sand and mud) has accumulated on the older transgressive sand and gravel sheet in southern Canterbury Bight.

A thick prism of modern muddy sand has accumulated in the northern part of Canterbury Bight. There, a secondary landward component of transport created by wind drift (Carter & Herzer 1979) and probably on-shore waves, confines the modern deposit to the inner shelf. The shallow upper portion of the deposit has been kept mud free (Fig. 11) by swell and storm waves. From it, sand is transported eastwards then northwards around Banks Peninsula.

Pegasus Bay is in the lee of Banks Peninsula, and sediment moving around the peninsula has accumulated in the bay along with sediment entering from the rivers to the west. Sand and mud have built up the floor of the southern part of the bay by at least 28 m and sand has formed a banner bank at the mouth of the bay (Figs 5, 10, 20). The sand on the bank does not cross to the western shore.

Tendency of Relict Sediments towards Hydraulic Equilibrium

The relict sediments on the shelf are adjusted to the present hydraulic environment, the degree of reworking being different in different places. The adjustment is shown most clearly by belts of palimpsest sand, and by deposits of gravel that are stripped of sand.

The coarse lithic gravel of the inner part of central Canterbury Bight is considered here to have been derived from underlying gravel outwash fans, and lies within the depth range that is frequently swept by wave-induced currents (Carter & Herzer 1979). Dispersal paths inferred from sea-bed drifters (Carter & Herzer 1979) are all away from this area. Sand and mud is thus continually swept out of the area and the gravel that remains is a lag deposit.

On the middle shelf in Canterbury Bight, gravel is extremely rare (Figs 10, 12), implying that currents are slower than on the inner shelf. Second-order ridges are low, and the more southerly ones appear to be inactive at the present time (*see* p. 61). However, the mud-free sand belt which occurs about 40 km off shore in this area (Fig. 10) forms a traction zone up to 1.7 m thick in cores (Herzer 1977, Appendix 4) and is evidently mobile. The sand here is made up of relict Mode III from the Canterbury Bight Formation, except near the southern margin of the mud-free belt, where the sand is frequently bimodal (Fig. 14) and contains Mode IV sand apparently derived from the Pegasus Bay Formation to the south. In one small area, about 45 km south of the Rakaia River, on the southern part of the inner zone of second-order ridges, Mode III disappears from the clean sand, which contains only Mode IV. This clean Mode IV sand is interpreted to be the northern edge of the Pegasus Bay Formation of southern Canterbury Bight. The edge of the modern blanket of muddy sediment thus changes north of latitude 44° 20′S to a mobile, clean Mode IV sand facies which is mixing with and ultimately replacing the coarser palimpsest Mode III sands.

Off Banks Peninsula, where the flows of currents are constricted and therefore stronger than elsewhere, the sand of the relict sediment on the middle shelf is being swept in the form of sand ribbons across lag pavements of gravel and shells (*see* p. 34). These mobile sand bodies are estimated from the variable thickness of the traction zone in cores (Herzer 1977, Appendix 4) to be up to 0.75 m thick. Second-order ridges are high and may still be active (*see* pp. 60-61). North of the peninsular constriction, currents are somewhat slower, ridges are absent, but the sand is locally mud-free in a traction zone of variable thickness up to 0.6 m thick (Herzer 1977, Appendix 4) and is still apparently mobile.

To the north-east, in the region of submarine canyons, the Mode III sand on the shelf edge terrace and upper continental slope is ascribed here to past or present sand spillover. Clean Mode III sand on the walls of the westernmost tributary of Pegasus Canyon suggests that spillover is taking place now.

The occurrence of relatively clean sand in isolation at the edge of the continental shelf (*see* p. 28) is unexplained. The energy to shift sediment there may come from internal waves or from accelerated tidal currents that are expected at the shelf edge (Carter & Herzer 1979).

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