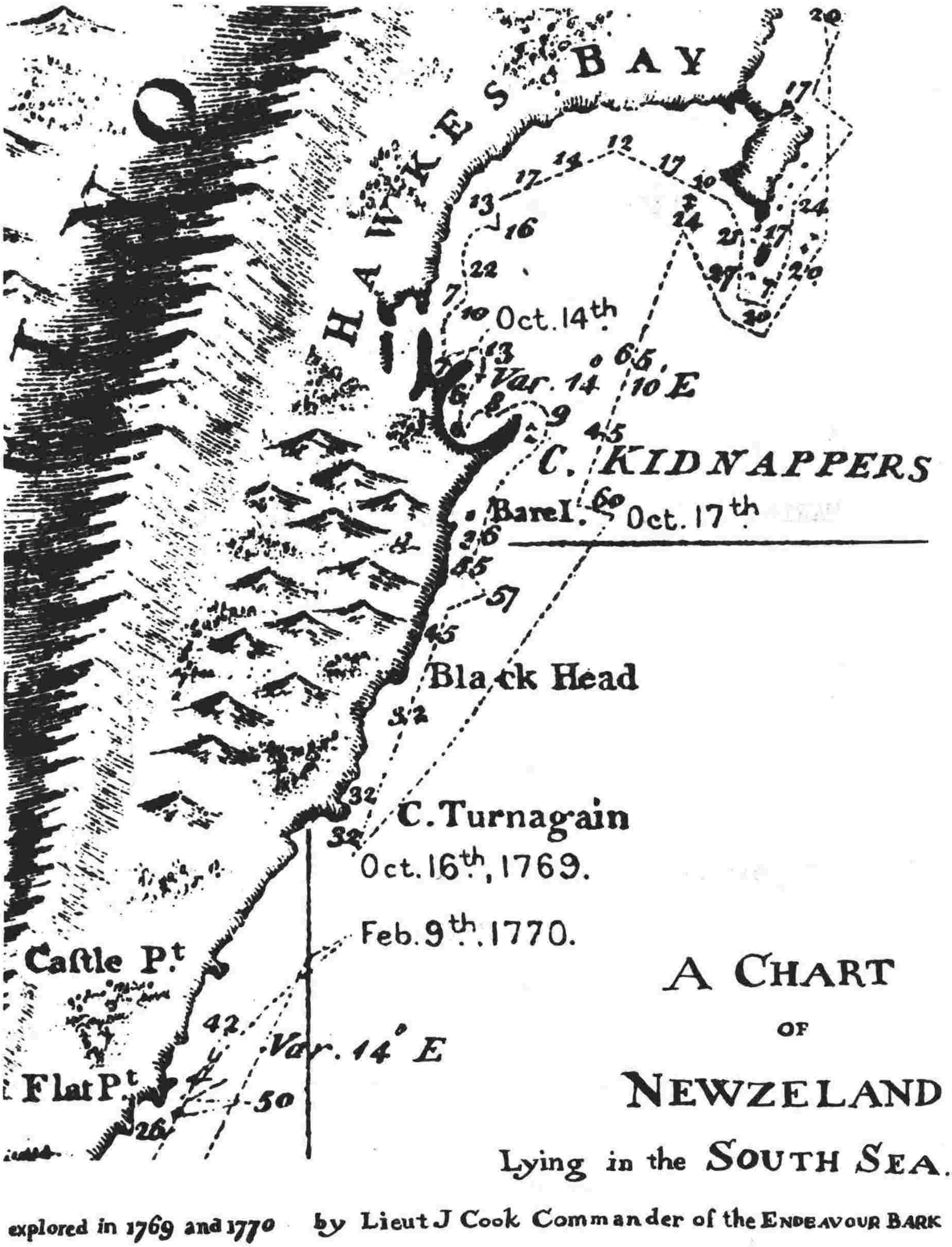

Frontispiece:

Enlargement of part of a 19th century engraving of Cook's Chart.

KEITH BRIAN LEWIS

MARINE GEOLOGY OF THE TURNAGAIN AREA

Thesis submitted for the degree of
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CHART TURNAGAIN SEDIMENTS in folder at back of thesis

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ABSTRACT

The Turnagain Area covers the continental shelf and slope off the east coast of North Island, New Zealand between Napier and Castlepoint. Its Late Quaternary stratigraphy, tectonic history, sedimentation and foraminiferal distribution are described with the aid of continuous seismic profiles, sediment samples and cores.

Results are presented in seven papers and a chart. The first three papers deal mainly with sub-bottom layers revealed by continuous seismic profiles; the next three papers describe dried sediment samples and cores and the last paper is a study of foraminifera in alcohol-preserved sediment samples. The topics discussed in each of the seven papers are as follows:

1. stratigraphy, sedimentation rates and origin of present topography on the continental shelf and upper slope;
2. rates of tectonic processes;
3. slumping;
4. distribution of sediments;

5. ages of indurated sediments;
6. ash horizons and rates of deposition on the lower part of the continental slope.
7. the distribution of living and dead foraminifera.

The chart shows bathymetry and nature of sediment at the seabed.

The sediments beneath the sea have been folding since Miocene times in the same way as marine sediments on the adjacent land. On the seabed anticlinal crests are preserved as ridges and banks and synclines form depressions. The present land area is rising and much of the seabed is sinking; the zero isobase between them is situated on the inner continental shelf. It has been at about the same position throughout Late Quaternary times, being always close to the dividing line between net erosion and net deposition. Rates of tilting have ranged from 2 to 36 microdegrees/thousand years and rates of vertical movement from +1.7 to -1.5 m/thousand years. Seaward of the zero isobase the continental shelf and upper slope has been built upwards and outwards by prisms of sediment, each prism representing a phase either of low sea level or of high sea level. Prisms deposited during periods of glacially lowered sea level are at their thickest beneath the upper slope; prisms deposited during periods of relatively high sea level are at their thickest beneath the continental shelf. Parts of the youngest prism on the upper slope have slumped on gradients as low as 1°.

The topography and sediments formed during the last 20 thousand years have received the most attention. The present continental shelf if a composite feature. The inner part has been formed by wave-planation of hard rock near shore and deposition of the latest prism of sediment offshore. The outer part and the shelf break were formed by wave-planation and by deposition during the last low sea level about 20 thousand years ago. At that time the shelf break ranged in depth from about 40m to about 70m, being shallowest where eroded into soft sediment and deepest where deposited beyond the seaward edge of erosion. In adjacent areas the shelf break was probably formed at depths of less than 20m being eroded into hard rock. The inner part of the wave-planed surface formed at that time is now deeply buried by the latest prism of sediment but the outer part is covered by only a thin veneer. The outer shelf is still essentially a drowned low sea level feature.

At the thickest part of the prism on the mid continental shelf, rates of deposition above an 8 thousand year old seismic reflector range from about 1 to about 4 m/thousand years, being most rapid south of major rivers. Rates are too slow to be measured at some places near the shelf break and at ridges on the continental slope. In depressions on the continental slope, sedimentation rates are indicated by the depth of the 3.4 thousand year old Waimihia ash and range from 0.36 m/thousand years in a depression relatively near land to 0.02 m/thousand years in the depression furthest from land. Sediments range from fine sand near shore to clayey fine silt on the lower slope. Many sediments are

bimodal because they were deposited as a mixture of floculated and unfloculated grains. Rapidly deposited sediment on the continental shelf is predominantly detrital sand and silt; slowly deposited sediment near the shelf break and on ridges consists mostly of volcanic ash, foraminifera, and glauconite. Muddy sediment in continental slope depressions contains sandy turbidite layers. Different environments are characterised by sediment types and foraminiferal faunas that can be matched in Tertiary Rocks.

GENERAL ACKNOWLEDGMENTS

During this study many people have willingly helped me with technical skill, advice, and encouragement. I am especially grateful to Mr J.W. Brodie, Professor P. Vella and Professor W.H. Wellman, whose interest has immeasurably increased my own knowledge and enthusiasm and has promoted closer personal liaison between the N.Z. Oceanographic Institute and the Geology

Department at Victoria University. Mr Brodie and Prof. Vella have constructively criticised drafts of all papers in this thesis. Prof. Wellman has advised me on many aspects of local land geology and on the interpretation of continuous seismic profiles. He has contributed much of his time to showing me the coastal geology of Hawkes Bay and Wairarapa, to discussing problems relating to the correlation of land and submarine geology and to editing many drafts of the first two papers. My colleagues at the Oceanographic Institute and fellow research students at Victoria University have added much to the interest of the work by their willingness to discuss its various aspects.

I am indebted to the officers and crew of m.v. Taranui for their enthusiastic cooperation during collection of data at sea. I must express my admiration for their courage and seamanship during the worst storm in New Zealand's recorded history, the "Wahine" storm of April 10th 1968.

The staff of the New Zealand Oceanographic Institute have given freely of their considerable technical skill. Mr E.J. Barnes and Mr N. Lambert rebuilt seismic equipment destroyed in the "Wahine" storm in time for a cruise later the same year, and they supervised its operation at sea. Miss C. Jenkins, Miss A. Doyle and Mr R. Grapes assisted with grain-size analyses of sediments. Miss P. Lawrence drafted most of the figures and Mrs R.M. Thompson typed the text.

My wife has helped in many ways including typing initial drafts and checking references and I am particularly grateful for her encouragement and forbearance during the final stages of the work.

GENERAL INTRODUCTION

GENERAL SETTING

The area studied is part of the continental shelf and slope of the east coast of North Island, New Zealand. It corresponds with the area covered by the Turnagain Coastal Series Chart published by the New Zealand Oceanographic Institute (Lewis and Gibb 1970, in pocket at back of this thesis). Its northern boundary is latitude 39°30'S, which intersects the coast at Napier City; its southern boundary is latitude 41°00'S, which intersects the coast near Castlepoint, and its eastern boundary is longitude 178°00'E. Its area is about 15000 km^2.

Land to the west of the study area is tectonically highly active and dominanted by a NNE trending, axial range of mountains (frontispiece). The range is composed mainly of well indurated, Mesozoic "greywacke" rocks. Beyond it, to the west, is an area of active volcanoes. Between the axial range and the coast lie alluvial plains and coastal hills, the latter being composed of Tertiary and Quaternary mudstone, sandstone and limestone. The coast trends almost parallel to the axial range except at the large re-entrant of Hawke Bay.

Immediately to the east of the study area, at a depth of 3000 m, is the NE trending trough which has been named the Hikurangi Trench and beyond it is the undulating floor of the Pacific Basin ranging in depth from 2500 - 5000 m.

PREVIOUS WORK

In October 1769 Lieut. James Cook, commanding the bark Endeavour, made landfall at Poverty Bay, 80 km to the north of the study area. He sailed southwards as far as the white cliffs of Cape Turnagain charting the coast and sounding the adjacent seabed. On his chart he named many conspicuous features on the coast such as Hawke's Bay, Cape Kidnappers, Bare Island and Black Head. At Cape Turnagain he turned northward again to start his circumnavigation of North Island, recognising the same white cliffs once more in February 1770. Cook's chart is recognised as one of the finest examples of naval hydrography : Admiral Wharton, Hydrographer of the Navy wrote that "Never has a coastline been so well laid down by a first explorer" (Ross 1969). On modern charts possessives are eliminated from names of hydrographic features. Thus Cook's name Hawke's Bay becomes Hawke Bay although the original name is retained for Hawkes Bay Land District, the apostrophe usually being dropped.

Before Cook's visit New Zealand was scarcely known to the outside world. Abel Tasman had sailed along the west coast more than a century before Cook but Cook may not even have been the first explorer of the east coast. Maori legend has it that, in the tenth century, the Polynesian explorer, Kupe and his navigator, Reti returned to their homes near Tahiti with descriptions of the general shape of North Island, descriptions of some conspicuous coastal features and sailing directions to New Zealand. These sailing directions are supposed to have been followed by later colonisers (McLintock 1966). There is also some evidence that either Portuguese or Spanish explorers sailed down the east coast of North Island. The evidence is based on an imaginative interpretation of crude 16th century charts, on an ancient Spanish-type helmet dredged from Wellington Harbour and on a ship's bell inscribed in Tamil that was used for many years as a cooking pot by North Island Maoris (Maling 1969; Ross 1969).

During the 80 years after Cook's exploration the British and French navies added details to the chart of the study area. In 1827 the French navigator Dumont D'Urville sailed northwards in the Astrolabe along the east coast but added little to Cook's work. He made the interesting observation that the sea became progressively more discoloured as he sailed from Bare Island to Cape Kidnappers and he attributed the discolouration to rivers (then undiscovered) in Hawke Bay (Wright 1950).

The first concerted programme after Cook's time was the "Great Survey" between 1848 and 1855, (Ross 1969) begun by Capt. J.L. Stokes, on the Acheron and completed by Cdr Byron Drury on the Pandora. The "Great Survey" revealed the extent of the continental shelf and the presence of some irregularities on the continental slope. The Challenger Expedition in 1874, obtained the first sample of mud from the lower continental slope in the study area (Murray 1895).

The most recent hydrographic survey was completed in 1956 under the supervision of Cdr G.S. Ritchie, commander of the Lachlan. The ship was equipped with an echo-sounder to measure depth and radar beacons for fixing positions at sea.

In the 1960's oceanographers joined naval hydrographers in the study of the seabed. The Lachlan resurvey provided data for Pantin's (1963) contoured bathymetric charts and his descriptions of major bathymetric features. These features include a narrow continental shelf, which is 15 - 20 km wide south of Hawke Bay and 60 km wide at Hawke Bay, a relatively deep shelf break at 200 m deep, a continental slope with NNE trending ridges and depressions and an unusually steep-sided depression and canyon system off the Porangahau River. Pantin (1967) mapped bottom sediments in Hawke Bay and a seismic reflector at 0 - 20 m beneath the seabed. Continuous seismic profiles recording reflectors at hundreds of metres beneath the continental slope, reveal that the ridges on the continental slope are anticlinal and that the depressions are synclinal (Houtz et al 1967). Sedimentological studies by Pantin (1967, in press) include descriptions of organic and sedimentary structures in piston cores. Pantin (1969) also determined that the greenish hue of many sediments is caused by organic compounds and ferric iron compounds adsorbed on clay minerals. Using X-ray diffraction techniques, Seed (1968) showed that clay-sized material in glauconitic sediments do not contain the degraded clay lattices that she considers to be suitable parent materials for glauconite.

PRESENT STUDY

The Turnagain area was chosen for a comprehensive marine geological study because it appeared to include environments representative of most of the Tertiary and Quaternary marine strata now forming the adjacent land. Continuous seismic profiles were obtained to determine the structure beneath the seabed. Surface sediment samples and piston cores were collected to aid interpretation of the profiles and to determine Holocene patterns of deposition. Selected sediment samples were preserved in alcohol for study of the distribution of benthonic foraminifera.

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PAPER 1

WAVE PLANATION AND OFFSHORE DEPOSITION DURING LATE QUATERNARY OSCILLATIONS OF SEA LEVEL : NAPIER TO CASTLEPOINT, NEW ZEALAND.

Accepted for publication in N.Z. Jl Geol. Geophys. 1971

ABSTRACT

Continuous seismic profiles of the continental shelf and upper slope show the effects of sea level changes on submarine topography and stratigraphy during the last few glacial and interglacial ages. Beneath the continental shelf the profiles show four unconformities that were formed by wave planation and later burial. The four unconformities separate five stratigraphic units, in order of increasing age: 1. the Acheron Formation, which is at its thickest on the continental shelf and is correlated with post-glacial rising and high sea level; 2. the Britomart Formation, which is at its thickest on the upper continental slope and is correlated with last glacial low sea level; 3. the Cook Formation, which is at its thickest beneath the continental shelf and is correlated with last interglacial high sea level; 4. the D'Urville Formation, correlated with the penultimate glacial low sea level and the penultimate interglacial high sea level; 5. the oldest unit, Middle Quaternary and older strata.

Late Quaternary stratigraphy is interpreted

in terms of migrations of a zone of wave planation and a parallel zone of rapid offshore deposition across a seaward tilting substrate. When eustatic sea level falls the zones migrate seawards and the outer continental shelf is wave planed. When sea level rises they migrate landwards and the inner continental shelf is buried by sediment. When sea level remains stable for a long time the zones migrate to positions such that the rising inner shelf is being wave planed and the subsiding outer shelf is being buried.

Thus, the inner part of the continental shelf was formed by nett erosion of rising Mid Quaternary and older rocks and the outer part was formed by Late Quaternary sediments building upwards and outwards on a subsiding basement. The present topography of the outer part of the shelf is largely a result of wave planation and offshore deposition during the last low sea level and the topography of the inner part is a result of present wave planation and present burial of low sea level topography.

Highest average rates of deposition at any time occur along a line that is 5-20km from shore. During the last glacial age the line was on the upper continental slope; at present it is on the inner or middle continental shelf. At each time, rates of deposition on the line have ranged from about 1 to 4m per thousand years. The amount of sediment that is being deposited at present on the shore, continental shelf and continental slope is equivalent to subaerial erosion at an average rate of 0.5m per thousand years, from the catchment of all rivers draining into the areas.

INTRODUCTION

During the Late Quaternary, growth and melting of the ice caps caused large eustatic changes in the level of the sea. Topographic and stratigraphic effects of the sea level changes have been studied on land in many parts of the world and can now be studied beneath the sea by means of a high resolution continuous profiler.

Profilers have already revealed the effects of the post glacial rise of sea level (Moore and Shumway 1959; Moore 1960; Allen 1963; Van Andel and Sachs 1964; Golik 1968) and some of the effects of low sea level such as development on the outer shelf of deltas (Curray and Moore 1964; McMaster et al 1970), wave-cut cliffs and river channels (Ewing et al 1963; Knott and Hoskins 1968). The following study shows the effects of sea level changes on erosion and deposition since the Antepenultimate glaciation.

A profiler capable of recording horizons not less than 2m apart (Barnes 1970) was used to obtain profiles of the continental shelf between Napier and Castlepoint and the adjacent continental slope to a depth of 800m (Fig. 1). Pantin (1963) has described the morphology of the area. The continental shelf is narrow (15-60km), steep (0.1-0.7°) and has a relatively deep (200m) shelf break. The upper continental slope has ridges and banks that are shown here to lie on an anticline. Pantin (1966) has also described the surface and near-surface sediments of Hawke Bay including a reflective horizon several metres below the seabed and four

FIGURE CAPTION

FIGURE 1

Chart of the coast, continental shelf and slope east of North Island, New Zealand showing the positions of the continuous seismic profiles. Thick numbered lines show positions of profiles illustrated in Figs 2, 3, 5, 6. Depths are in metres.

Inset : Map of New Zealand showing position of the study area.

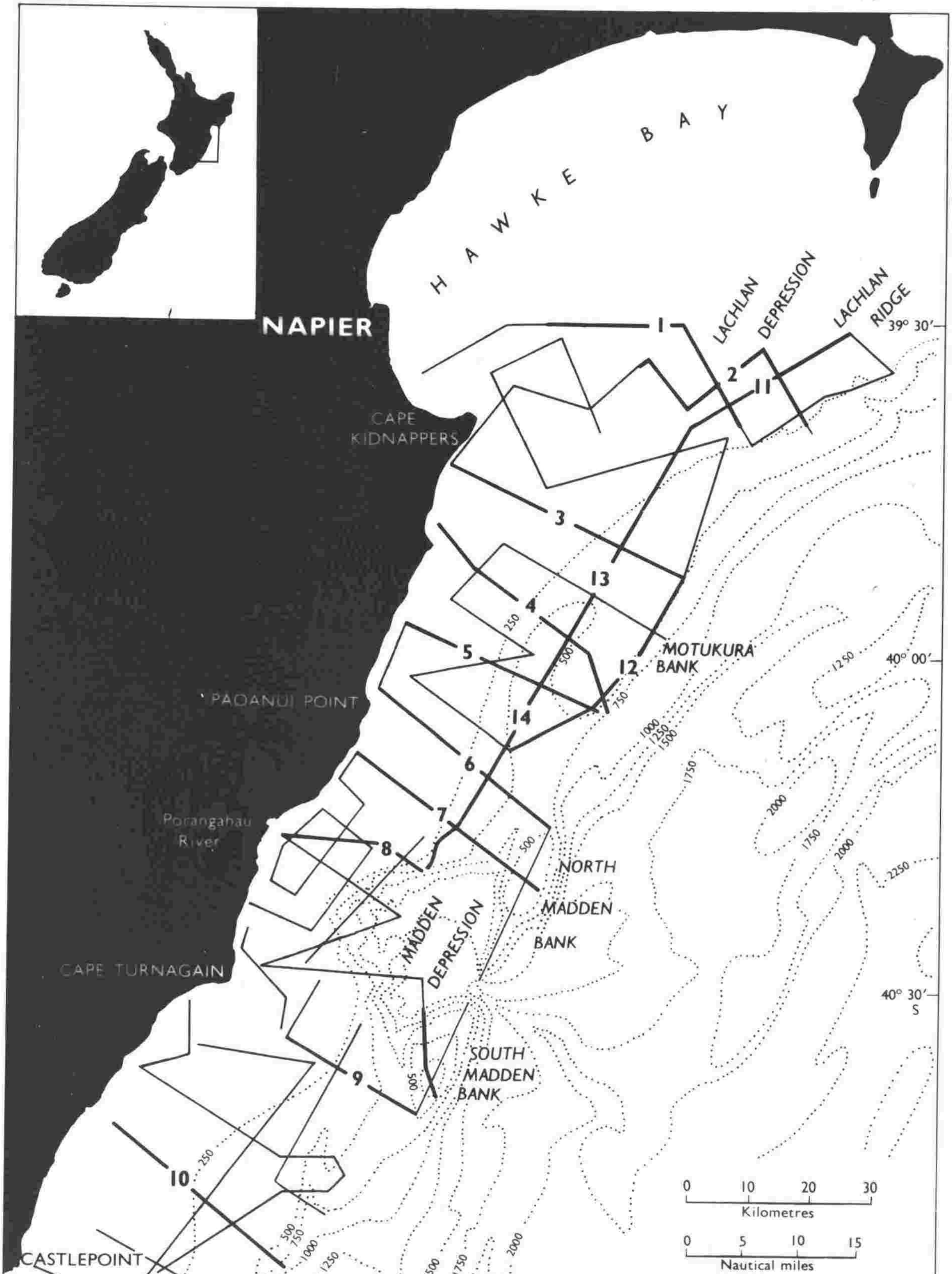

NAPIER
HAWKE BAY
LACHLAN DEPRESSION
LACHLAN RIDGE
39° 30′
CAPE KIDNAPPERS
1
2
11
3
13
4
5
12
MOTUKURA BANK
40° 00′
PAOANUI POINT
14
6
7
Porangahau River
8
NORTH MADDEN BANK
MADDEN DEPRESSION
CAPE TURNAGAIN
40° 30′ S
SOUTH MADDEN BANK
9
10
CASTLEPOINT
250
500
750
1000
1250
1500
1750
2000
2250
0 10 20 30
Kilometres
0 5 10 15
Nautical miles
176° 30′
177° 00′
177° 30′ E

Fig. 1

radiocarbon dated core samples. The surface sediments of the larger area that is examined here were charted by Lewis and Gibb (1970) and described by Lewis (in press, a). The profiles that are used in this study are used elsewhere (Lewis, in press b) to determine the growth rates of Late Quaternary folds.

COLLECTION OF PROFILES

Continuous seismic profiles were obtained from about 1500km of ships tracks (Fig. 1) using a sound reflection system with a 1 kilojoule Edgerton "boomer" as sound source (Barnes 1970). In water deeper than about 100m echoes were detected by 20 EVP-23 hydrophones in a 30m long plastic tube towed well astern of the ship. In shallow water only ten hydrophones were used. Signals of frequency 100-2000Hz were recorded by a Westrex Mk XV precision depth recorder which was set to the range of 0-800m; sound was assumed to travel at 1.5km/sec. both in seawater and in sediment. The most deeply buried horizon that was recorded was 300m beneath the seabed.

Outgoing impulses were triggered at intervals of two seconds, so that, at normal ship's speeds of 5-8 knots, they were 5-8m apart. Reflections from each outgoing pulse produce a vertical line of burn marks on the recording paper. Burn marks from successive pulses are side by side and merge to produce horizontal or sloping lines which represent profiles of the seabed and the bedding planes in the underlying strata. The profiles have a vertical exaggeration of 11-17 times, depending on the ship's speed. Thus, lines that dip at 45° represent surfaces that dip at 5.5°-3.5° and lines that are almost vertical represent surfaces with a dip of more than 15°.

The theory of seismic profiling is based on the fact that sound waves are reflected from any surface where there is a change in acoustic impedance. Acoustic impedance is the product of compressional wave velocity and bulk density, both of which are related to mineralogy and porosity (Hamilton et al 1956; Shumway 1960a, b). Porosity is dependent on degree of compaction and grain size. Thus each line on the profiles represents a surface where there is a change of either mineralogy, or degree of compaction, or grain size. Some lines are produced by multiple reflections between surfaces but these lines are easily recognised because they show the same irregularities as a more gently dipping, higher line and because they cross other lines. Lines produced by multiple reflections are ignored in descriptions of the profiles. "Boomer" profiles are free of lines produced by bubble resonance. At a surface where there is a large change of acoustic impedance, for instance at the top of a sand or gravel layer, most sound energy is reflected and little penetrates to lower horizons. Hence the surface is represented on the profiles by a thick line and underlying horizons are masked.

DESCRIPTION OF PROFILES

The profiles that form the raw data of this study are similar to the geological cross sections that are the final product of mapping projects on land. However, the geological cross sections have a legend to explain them whereas the profiles have no such legend and have to be interpreted from the configuration of reflective horizons and from the supplementary data of grab and core samples.

Most of the profiles are at right angles to the coast (Fig. 2) but these are linked by a few profiles along the upper continental slope (Fig. 3). Thus the three-dimensional configuration of some horizons is shown by the profiles because the horizons can be traced either along reflective horizons or along "phantom" horizons that lie between reflective horizons.

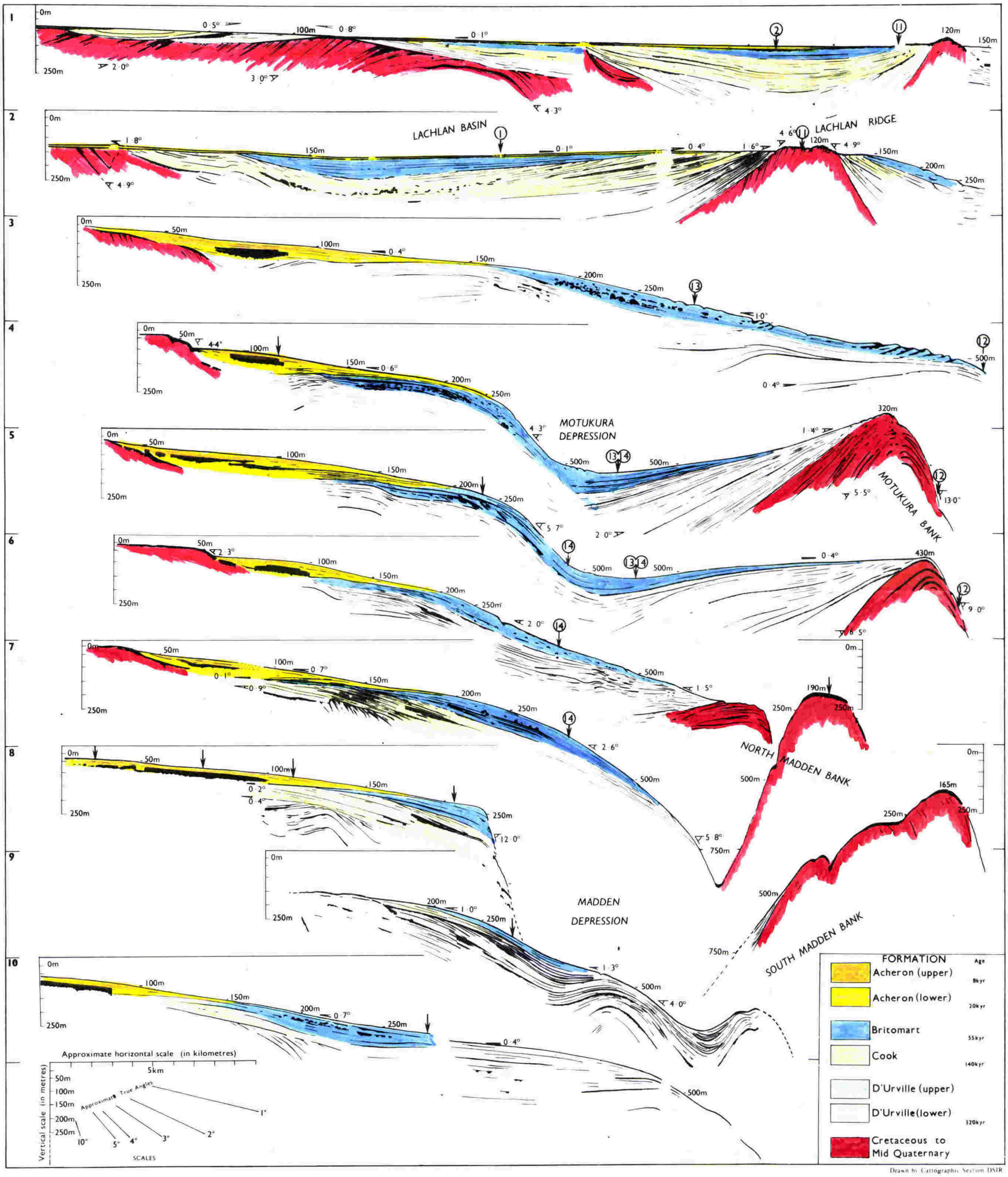
The horizons shown by the profiles define the boundaries of beds. Profiles at right angles to the coast (Fig. 2) show that, in general, beds dip away from the coast and away from offshore ridges which are proved, therefore, to be anticlinal. Young beds thin to nothing and old beds crop out at the coast and at the anticlinal offshore ridges (Fig. 4).

Some of the young beds are at their thickest beneath the middle and outer continental shelf

FIGURE CAPTION

FIGURE 2

Tracings of continuous seismic profiles from west (left) to east (right) coloured to show Upper Quaternary formations and "basement" of Middle Quaternary and older rocks. Formations coloured yellow were deposited during periods of high sea level. Those coloured blue were deposited during glacial periods of low sea level. Red indicates "basement" of Middle Quaternary and older rocks. Beds that are not coloured are of undetermined (but probably Quaternary) age. Positions of profiles are shown in Fig. 1. Photographs of some profiles are shown in Figs 5, 6. The type profile is the right half of profile 2. Unconformities can be seen beneath continental shelf in many profiles. Vertical scale in metres and dip scale in degrees assuming velocity of sound is 1.5km/sec. Horizontal scale in kilometres is correct to within 12% for any profile. ~~Numbered~~ Arrows indicate positions at which profiles are crossed by other profiles. Multiple reflections have been ignored.



Drawn by Cartographic Section DSIR

Fig. 2

FIGURE CAPTION

FIGURE 3

Tracings of continuous seismic profiles from south (left) to north (right) coloured as Fig. 2. Vertical, horizontal and dip scales as Fig. 2. Numbered arrows indicate position at which profiles are crossed by other profiles.

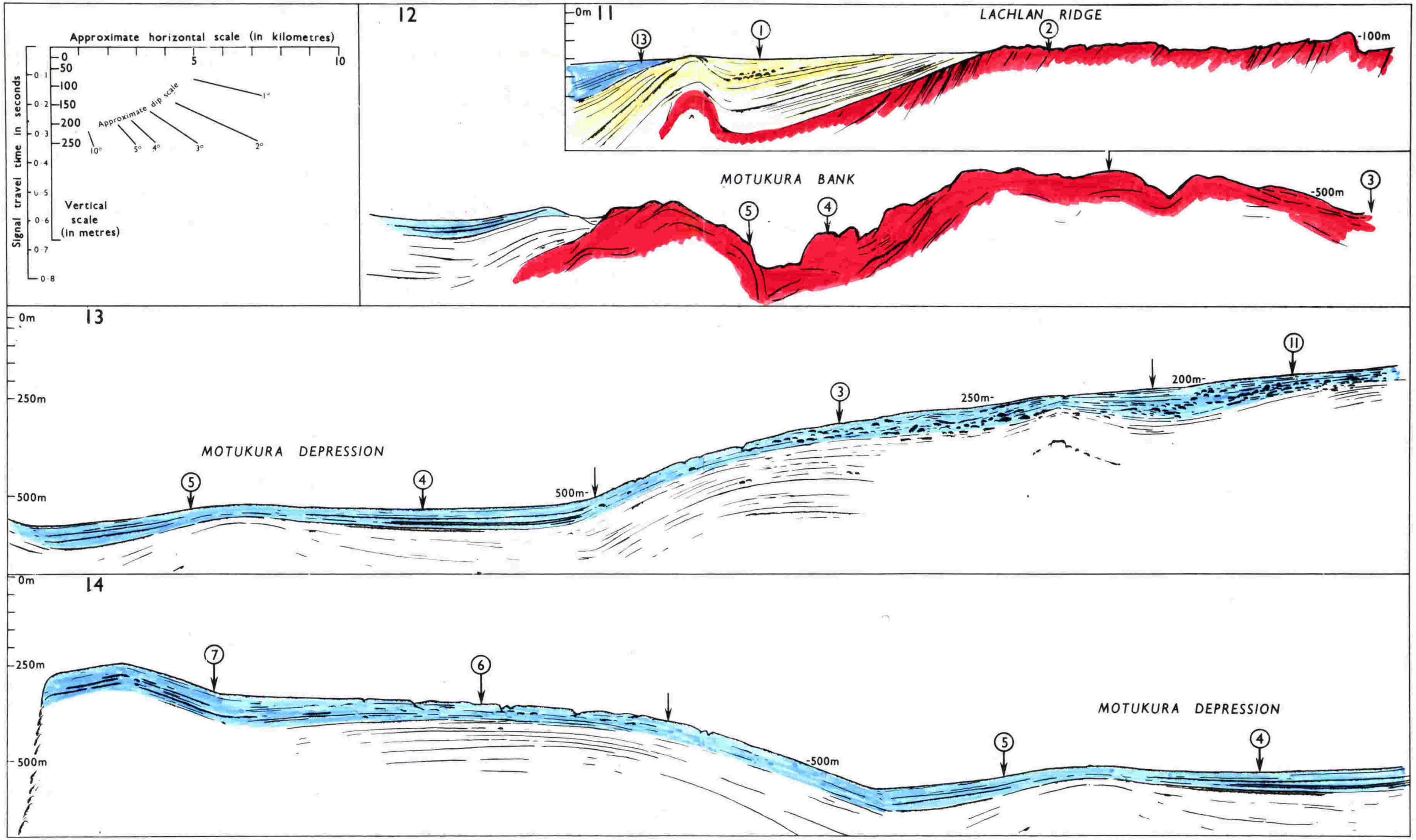
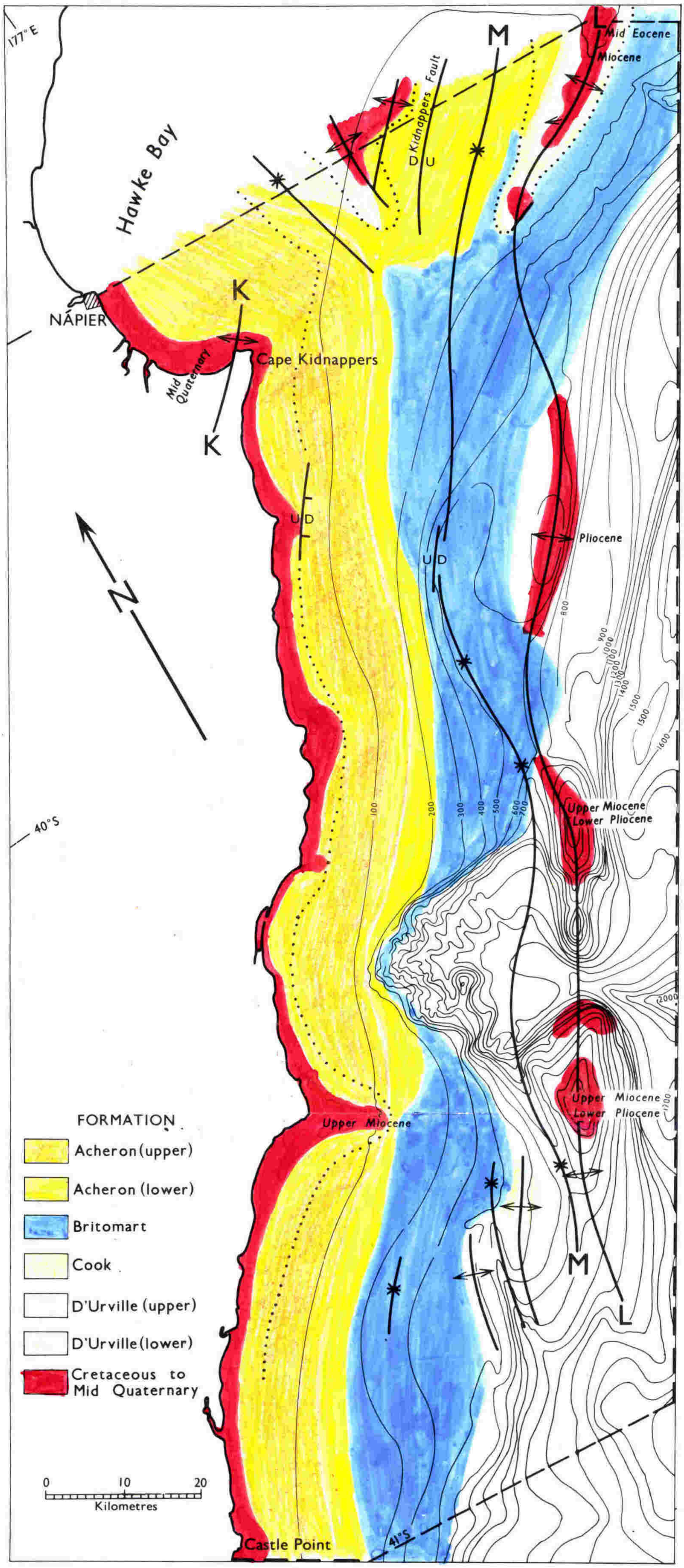

Approximate horizontal scale (in kilometres)
0
5
10
Signal travel time in seconds
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0
50
100
150
200
250
Vertical scale (in metres)
Approximate dip scale
10°
5°
4°
3°
2°
1°
12
11
0m
LACHLAN RIDGE
⑬
①
②
-100m
MOTUKURA BANK
⑤
④
-500m
③
13
0m
250m
500m
MOTUKURA DEPRESSION
⑤
④
500m-
③
250m-
200m-
⑪
14
0m
250m
500m
⑦
⑥
-500m
MOTUKURA DEPRESSION
⑤
④

FIGURE CAPTION

FIGURE 4

Geological map of the continental shelf and upper continental slope showing type of sediment 5m beneath the seabed. Coloured as Fig. 2, 3. Ages on banks are of foraminifera in rock samples (Lewis, in press c). Dotted line is zero isobase between rising landward area and subsiding seaward area. K-K is the Kidnappers Anticline; L-L is the Lachlan Anticline; M-M is the Mahia Syncline. Depth in metres.


177° E
Hawke Bay
NAPIER
M
L
Mid Eocene
Miocene
Kidnappers Fault
D U
K
Cape Kidnappers
Mid Quaternary
K
U D
U D
Pliocene
N
800
900
1000
1100
1200
1300
1400
1500
1500
1600
40° S
100
200
300
400
500
600
700
Upper Miocene
Lower Pliocene
2000
Upper Miocene
Lower Pliocene
1300
Upper Miocene
M
L
FORMATION
Acheron (upper)
Acheron (lower)
Britomart
Cook
D'Urville (upper)
D'Urville (lower)
Cretaceous to Mid Quaternary
0
10
20
Kilometres
41° S
Castle Point

(coloured yellow in Fig. 2). These include the most recently deposited beds which are almost absent from the upper continental slope. Others are at their thickest beneath the continental slope (coloured blue in Fig. 2). All young beds dip at less than 6°. They are acoustically transparent so that reflections are still recorded even where reflective horizons are deeply buried. At some places, they are truncated at smooth horizons.

The old beds (coloured red in Fig. 2), which dip more steeply than overlying young beds, are acoustically opaque and, at places, are truncated at irregular, highly reflective horizons.

Beneath the continental shelf young beds lie unconformably on old beds and contain several unconformities (Fig. 2, profiles 2, 7, 8, 9). The angular difference across each unconformity within the young beds is, in general, less than 1°, and it decreases towards the shelf edge so that, beneath the upper continental slope, beds are conformable. All the unconformities except the youngest are almost planar surfaces that have been truncated on the middle continental shelf. The youngest unconformity extends on to the inner continental shelf and only its outer part is planar. At any place older unconformities dip more steeply than younger unconformities.

INTERPRETATION OF PROFILES

The old beds that crop out on the inner continental shelf are considered to be of similar age to the rocks on the adjacent shore. In southern Hawke Bay sandstones and conglomerates that form 100m high cliffs along the shore are of Middle Quaternary (Castlecliffian) age and beds on the inner continental shelf, which have a similar westward apparent dip of several degrees (Fig. 2, profile 1), are assumed to be of similar age. To the south of Hawke Bay limestones and mudstones dredged from the inner continental shelf are of similar types to those on shore and one sample from off Cape Turnagain has been dated as being of Upper Miocene age (Lewis, in press c). The old beds that crop out on the anticlinal offshore ridges have been sampled and are Tertiary mudstone (Fig. 4); two samples from the north of the study area are of Eocene age (Pantin 1966); eight other dated samples range from Upper Miocene to Lower Pliocene in age (Lewis, in press c).

The young beds shown in the profiles are considered to be of Upper Quaternary age because they overlie Middle Quaternary beds in southern Hawke Bay. The most recently deposited beds, which form a prism of sediment on the continental shelf, are correlated with the prism of "post-glacial" sediment that lies beneath the continental shelves of California (Moore and Shumway 1959; Moore 1960), Nigeria (Allen 1963, Venezuela (Van Andel and Sachs 1964) and Panama (Golik 1968). The prism of post-glacial sediment lies at the site of the present zone of rapid deposition. Older beds that are at their thickest beneath the continental shelf were also formed when the zone of rapid deposition was near its present position. Beds that are at their thickest on the upper continental slope were formed when the zone of rapid deposition had migrated seaward of its present position.

The unconformities are considered to be wave-planed surfaces that have been buried. The position of the rock outcrops on the innermost continental shelf correspond to the present position of a zone of wave planation. The wave-planed surfaces were formed when the zone of wave planation was located seaward of its present position.

The zone of wave planation and the zone of rapid deposition have migrated together during the Late Quaternary Period. The zones roughly parallel the present shore; their migration in a direction normal to the shore could have been caused by either eustatic oscillations of sea level or by tectonic oscillations of the seabed. It is known that sea level has oscillated during Late Quaternary time and it can be assumed that the direction of vertical movement has remained, in general, the same at any place. The lateral migrations of the zones are, therefore, correlated with eustatic oscillations of sea level.

Because the old wave-planed surfaces dip more steeply than the youngest one and more steeply than the slope at which they would be expected to form the wave-planed surfaces are considered to have formed on the flanks of three growing folds. The folds all trend NE-NNE and have been named, from west to east, the Kidnappers Anticline, the Mahia Syncline and the Lachlan Anticline (Fig. 4; Lewis, in press b). In Hawke Bay the axes of all three folds are on the continental shelf but to the south of Hawke Bay the axis of the Kidnappers Anticline is on land and the axes of the Mahia Syncline and the Lachlan Anticline are on the upper continental slope. Most of the continental shelf is tilting seawards and the zero isobase* extends along the inner and middle continental shelf, separating a rising landward area from a subsiding seaward area (Fig. 4). Thus, on the continental shelf seaward

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* An isobase is "a line connecting points of equal deformation" (de Geer 1892). A zero isobase is a line showing where nett vertical movement has been zero during a specified period, eg. in this case, since the Penultimate Glacial Age (Lewis, in press b). It is not an "axis of rotation", which passes through a body, nor is it a "hinge line" which separates two zones with different rates of tilting.

of the zero isobase erosional and depositional surfaces are downdropped and buried and thereby preserved from subsequent erosion. The buried surfaces have been tilted sufficiently to be distinctly different in dip and in depth. Thus, because of rapid tilting the topographic and stratigraphic effects of Late Quaternary oscillations of sea level are clearly recorded. This is in marked contrast to the poor Late Quaternary record in tectonically stable areas.

UPPER QUATERNARY STRATIGRAPHY

Type Profile

Buried wave-planed surfaces are most numerous and most clearly defined in a profile from the Lachlan Depression and the Lachlan Ridge (Fig. 2 , profile 2, Fig. 5a). This profile is selected as the type for defining the Upper Quaternary stratigraphic sequence.

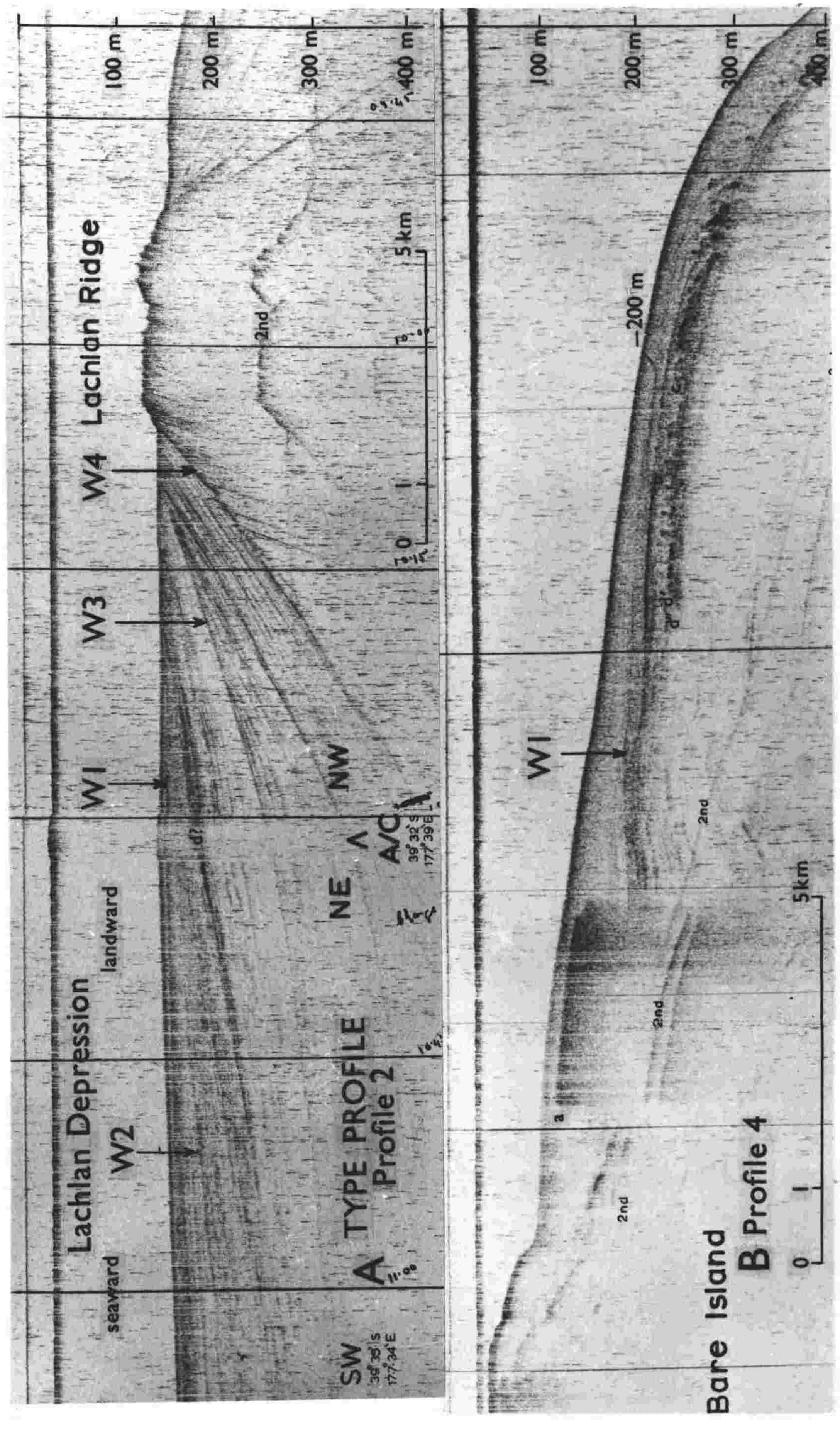
In the type profile there are four wave-planed surfaces, in order of increasing age, W1,

FIGURE CAPTION

FIGURE 5

Photographs of continuous seismic profiles. Positions shown in Fig. 1. A : Type profile; part of profile 2 showing tilted Late Quaternary unconformities on the flanks of the growing Lachlan Anticline. The unconformities are buried wave-planed surfaces of supposed Last Glacial (W1 and W2), Penultimate Glacial (W3) and Antepenultimate Glacial (W4) age. Depth in metres assuming velocity of sound is 1.5km/sec. A/C is at a change of course. B : part of profile 4 showing W1 and strongly reflective patches a, b, c, d, d" which can be correlated with similar patches in adjacent profiles, "a" is strongly reflective part of horizon that separates upper and lower parts of the Acheron Formation.

Fig. 5


Lachlan Depression
seaward
landward
Lachlan Ridge
W2
W1
W3
W4
100 m
200 m
300 m
400 m
0
1
5 km
d?
2nd
SW
39°35'S
177°34'E
A
TYPE PROFILE
Profile 2
NE
A/C
39°32'S
177°39'E
NW
Bare Island
B
Profile 4
—200 m
a
d'
5km

W2, W3 and W4 (Fig. 5a). The four wave-planed surfaces separate five stratigraphic units. The four upper units, which together form the Upper Quaternary sequence, are the Acheron Formation, the Britomart Formation, the Cook Formation and the D'Urville Formation*. The lowest unit consists of the highly reflective Tertiary strata that crop out on the Lachlan Ridge. The soft Upper Quaternary formations are truncated by W1 at a lower level than the hard Tertiary strata. Table 1 shows provisional correlations of the four Upper Quaternary formations with Late Quaternary events on land.

The angular difference across each of the three upper wave-planed surfaces decreases rapidly westward away from the Lachlan Ridge and gradually,

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* The proposed stratigraphic names commemorate ships and commanders that have played a role in the charting and sounding of the eastern side of New Zealand. Andrews and Hsu (1970) have suggested that submarine formations should, in general, be named after ships and that names should be applied in alphabetical order to formations in order of increasing age.

TABLE 1

Correlation of wave-planed surfaces and formations

Approx. age in thousand years	Wave-planed Surface	Formations	Geological Age	Possible Correlations	
				New Zealand	Europe
8	inner ↑	Acheron	Holocene	Aranuian Stage (warming and warmth)	Holocene
20	W1 outer		Last Glacial Age		Würm Glaciation
		Britomart		Otiran Stage (cooling and cold)	
55	W2				
		Cook	Last Inter-glacial		Eem Inter-glacial
120	Marine bench ↑			Oturian Stage	
140	W3		Penultimate Glacial Age		Riss Glaciation
		D'Urville		Waimaungan Stage ?	
			Penultimate Interglacial		Holstein Interglacial
				Terangian Stage	
			Antepenultimate Glacial Age		Mindel Glaciation
320	W4				
				Porikan Stage ?	

southward along the Lachlan Depression, away from land. At the southern end of the Lachlan Depression the angle decreases to zero and beds are conformable. The horizons that continue seaward from each of the three upper wave-planed surfaces are, in order of increasing age, W'1, W'2 and W'3.

Each formation and the beds within it become thicker away from the Lachlan Ridge. The Acheron Formation, the Cook Formation and the beds within the Cook Formation are at their thickest at the northern, landward end of the Lachlan Depression; whereas, the Britomart Formation and the beds within it are at their thickest at the southern, seaward end of the depression. The Acheron Formation represents sediment that is being deposited during the present period of high sea level and the Cook Formation is considered to represent sediment deposited during an earlier period of high sea level, probably the Last Interglacial Age. The Britomart Formation was deposited when the zone of rapid deposition was seaward of its present position, i.e. during a period of low sea level. Because it represents the youngest period of low sea level the Britomart Formation is correlated with the Last Glacial Age.

Acheron Formation

The top of the Acheron Formation is at the seabed; the bottom is either at the top wave-planed surface W1 or at the horizon W'1 that continues seaward from W1.

In Hawke Bay, W1 can be traced almost to the shore and to the south of Hawke Bay the highest wave-planed surface in each profile is correlated with W1. The inner part of W1, at depths of less than about 110m is much steeper than the outer part from 110m to about 170m. At most places the steep inner part is irregular and truncates beds correlated with the Mid Quaternary, Tertiary and Cretaceous rocks that crop out on land. The gently dipping outer part is smooth and at depths of more than 130m truncates Upper Quaternary strata. To seaward, the horizon W'1 is gently dipping and strongly reflective to a depth of about 200m; it is more steeply dipping and either weakly reflective or close to the seabed at greater depths.

The gently dipping outer part of W1 was probably eroded by waves as sea level fell towards its lowest level 19-20kyr* ago (Curray 1961). Erosion ceased when the rate of tectonic downdrop exceeded the rate of eustatic fall of sea level about 20kyr ago. If eustatic sea level 20kyr ago was 110m below present sea level as Curray (1961) suggests, then indurated Tertiary mudstones were eroded to within about 10m of that sea level and soft Upper Quaternary beds, which have subsequently been downdropped about 10m at their seaward edge (Lewis, in press a) were eroded to a depth of about 50m below the 20kyr old sea level. At the same time sediments, which have subsequently been downdropped by about 20m (Lewis, in press a) built out a planar surface to a depth of about 70m below the 20kyr old sea level.

The steep inner part of W1 was eroded subaerially while sea level was low and was wave-planed during and after the post-glacial rise of sea level. Its present surface is therefore diachronous, having

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* kyr = thousand years, the basic time unit for Upper Quaternary stratigraphy.

been formed between 20kyr ago and the present. A 2km wide bench, now at a depth of 50-75m around Cape Kidnappers and Bare Island, may have been formed during the stillstand that has been dated as 10kyr old by Pantin (1966) and Cullen (1967). The rock platform at a depth of less than 20m around the present headlands has probably formed since the rapid rise of sea level that ended about 7kyr ago (Wellman 1969).

The Acheron Formation, which lies above the wave-planed surface W1 and the horizon W'1, has been deposited during the time since the low sea level about 20kyr ago; radiocarbon dates of near-seabed sediments in the Lachlan Depression range from 15 to 2kyr (Pantin 1966). The Acheron Formation is considered to be the same age as the Late Würm and Holocene deposits in other parts of the world (and the Aranuian Stage (Suggate 1961) in New Zealand) (Table 1).

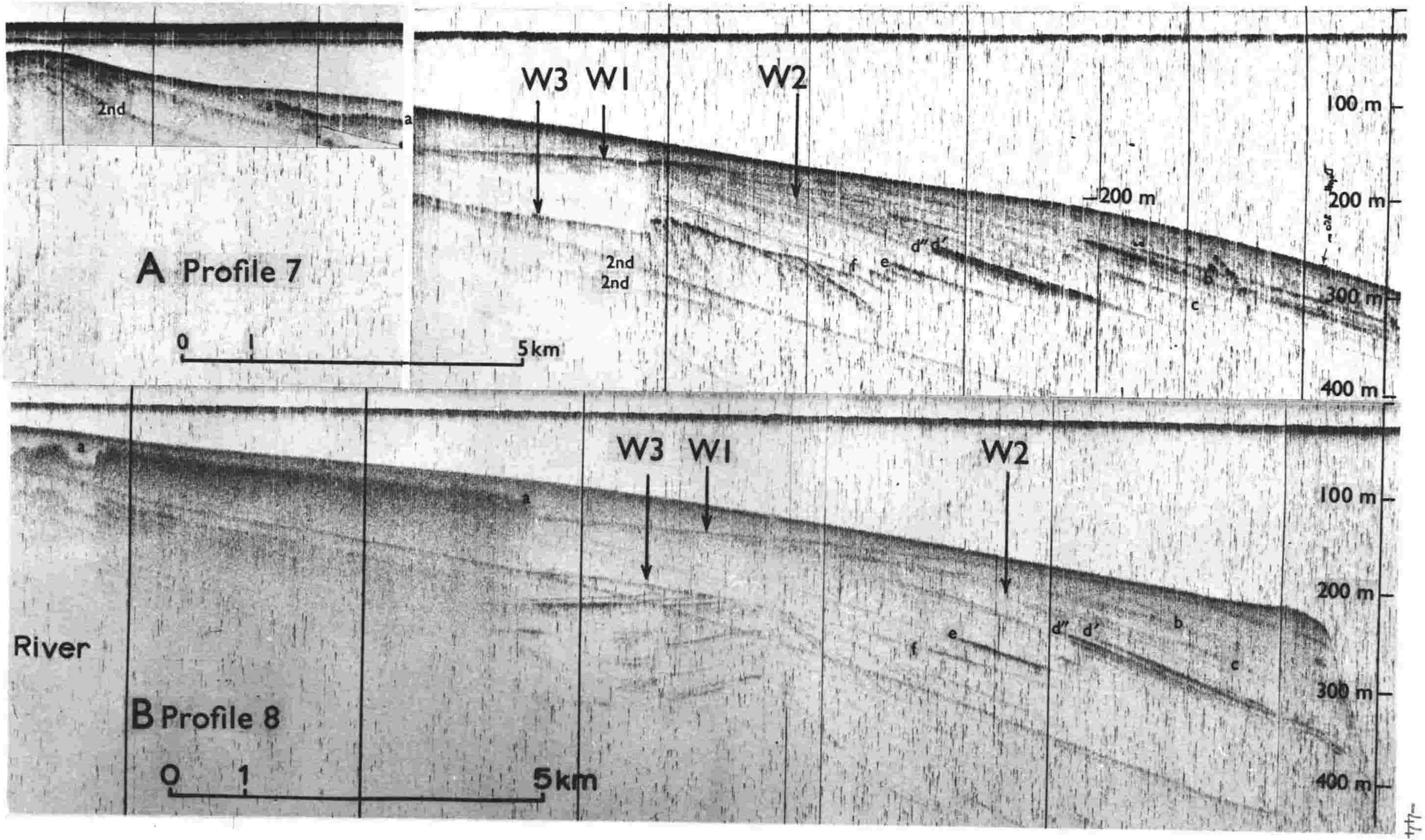
It is divided, by the highest reflective horizon in the profiles, into an upper unit and a lower unit. The highest reflective horizon, which appears to be in conformable beds, is strongly reflective beneath the inner and middle continental shelf and weakly reflective beneath the outer shelf (Fig. 5b, Figs 6a, b). The strongly reflective part of the horizon is 50-140m deep and 20-30m beneath the seabed at most places south of Hawke Bay. It is less deeply buried in southern Hawke Bay and it is correlated with a pebbly mud that crops out (Pantin 1966, 1967) on the seabed in central Hawke Bay. Pantin (1966) reported a radiocarbon age of 10kyr for a sand underlying the pebbly mud and suggested an age of 8kyr for the top of the pebbly mud. He also reported a radiocarbon age of 8.6kyr for "organic carbon" from about the same depth as the highest, weakly reflective horizon (Pantin 1966, plate 4) on the outer continental shelf of Hawke Bay. Pantin suggested that the "organic carbon" was derived, but it seems unlikely that any organic carbon could survive for more than a few centuries in a form capable of being redeposited. An age of 8kyr is accepted for both the highest reflector and the top of the pebbly mud. The strongly reflective horizon that Pantin (1966) charted appears to correspond, not with an 8kyr surface as he suggested,

FIGURE CAPTION

FIGURE 6

Photographs of continuous seismic profiles. Positions shown in Fig. 1. A : part of profile 7 showing wave-planed surfaces (W1, W2, W3) and strongly reflective patches (a, b, c, d' e, f); a is the top reflective horizon that separates the upper and lower parts of the Acheron Formation. B : part of profile 8 showing wave-planed surfaces and strongly reflective patches.

Fig. 6


A Profile 7
B Profile 8
W3
W1
W2
2nd
2nd
2nd
a
b
c
d'
d''
e
f
River
0
1
5km
100 m
200 m
300 m
400 m

but with the diachronous wave-planed surface W1 or a thin overlying sand.

Isopach charts (Fig. 7) show that both the upper and the lower units of the Acheron Formation are prisms of sediment with the thickest part of each prism almost parallel to the shore. The thickest part of the upper unit of the Acheron Formation ranges between 4 and 10km from shore and reaches a maximum thickness of 32m off the coast about 10km south of Cape Kidnappers (Fig. 7a). The thickest part of the lower unit of the Acheron Formation ranges from 6-13km from shore and reaches a maximum thickness of 46km about 30km south of Cape Kidnappers (Fig. 7b).

Britomart Formation

The top of the Britomart Formation is in part the top wave-planed surface W1 and in part horizon W'1; its base is similarly W2 and W'2. Most of the formation was deposited during a period of moderately low sea level that is correlated with the Last Glacial Age. The underlying and overlying wave-planed surfaces were eroded during periods of

FIGURE CAPTION

FIGURE 7

Maps showing thicknesses of A. the upper part of the Acheron Formation (0-8kyr*); B. the lower part of the Acheron Formation (8-20kyr); C. the Britomart Formation (20-55kyr). Black lines are isopaches in metres assuming velocity of sound in sediment is 1.5km/sec. Grey lines are depths in metres to base of each unit.

* kyr = thousand years.

Hawke Bay
LACHLAN RIDGE
LACHLAN BANKS
MOTUKURA DEPRESSION
MOTUKURA BANK
MADDEN DEPRESSION
TURNAGAIN BANKS
TURNAGAIN SEA VALLEY
39° 30'
177° 30'
177° E
40° S
40° 30'
176° 30'
A
B
C
Present land
Strong reflector (Fig. A)
Gently dipping parts of wave-planed surface W1(Fig B)
Wave-planed surface W2 (Fig C)
0 10 20 Kilometres

extremely low sea level that are correlated with the early and late stadials of the Last Glacial Age. The early stadial of the Last Glacial Age has been dated at about 55kyr (Gross 1964; Coope and Sands 1966; Van der Hammen et al 1967). Thus the Britomart Formation represents only that part of the Last Glacial Age between the early and the late stadials and ranges in age from 55kyr to 20kyr.

It is traced along the upper continental slope from near the type profile to the northern end of the Madden Depression (Fig. 3, profiles 13, 14) and from the upper slope landward to the continental shelf (Fig. 2, profiles 3, 4, 5, 6, 7). From the continental shelf near the northern end of the Madden Depression the Britomart Formation is correlated from profile to profile southward to midway between Cape Turnagain and Castlepoint (Fig. 2, profiles 7, 8, 9, 10; Fig. 6). W2 is recognised in profiles from the Lachlan Depression (Fig. 2, profile 2) and from Paoanui Point to Cape Turnagain (Fig. 2, profiles 7, 8; Fig. 6) but nowhere is it as conspicuous as either W1 or W3.

An isopach chart (Fig. 7c) shows that the Britomart Formation is a prism of sediment that is thickest on the upper slope at a depth of about 300m and at a distance from shore of 20-25km. The maximum thickness of the prism, which occurs on the upper continental slope 40km south of Cape Kidnappers, is 115m. The prism thins to nothing on the middle continental shelf where it has been wave-planed and it becomes thin on the continental slope at depths of more than about 700m. On the continental slope it either crops out at the seabed or is covered by a layer of sediment that is too thin to be distinguished on the profiles (Fig. 4).

Cook Formation

The Cook Formation is truncated by wave-planed surfaces W1 and W2 and overlies the conspicuous wave-planed surface W3 which can be recognised only in the Lachlan Depression (Fig. 2, profiles 1, 2) and south of Paoanui Point (Fig. 2, profiles 7, 8, 9, 10).

The oldest beds of the Cook Formation are, like the beds of the Acheron Formation, at their thickest beneath the middle continental shelf. Thus they were probably deposited during a period of rising and high sea level. However, the youngest beds are thickest beneath the outer shelf and were deposited, therefore, during falling sea level. Thus the Cook Formation represents the period of rising, high and falling sea level preceding the early stadial of the Last Glacial Age, that is, it represents mainly the Last Interglacial Age. It follows that the underlying wave-planed surface W3 was planed during the low sea level of the Penultimate Glacial Age. A well defined marine bench that is 100-210m above sea level near Cape Kidnappers may represent an inner part of W3, that is analogous to the presently eroding inner part of W1. Its inner edge was formed during the Last Interglacial Age and subsequently uplifted (Lewis, in press b).

On the continental shelf where the Cook Formation is truncated, its thickness has been controlled by rate of downdrop rather than by rate of deposition. In the southern part of the Lachlan Depression the Cook Formation is 2½ times thicker than the Britomart Formation. If it is assumed that the rate of downdrop in the Lachlan Depression is constant and that each wave-planed surface formed at a similar depth below present sea level then the Cook Formation took $2\frac{1}{2}$ times longer to accumulate than the Britomart Formation, that is, about ($2\frac{1}{2}$ x 35) = 85kyr. Thus W3 and the culmination of the Penultimate Glacial Age are estimated to be about (85 + 55) = 140kyr old. The culmination of the Penultimate Glacial Age has been dated by different authors at between 110kyr and 160kyr old (Broecker 1965) but most recent estimates (Veeh 1966; Broecker *et al* 1968) make the age older than 120kyr. Thus the estimate of 140kyr for the age of W3 is reasonable and the Cook Formation is considered to range in age from 140kyr to 55 kyr old.

D'Urville Formation

In Hawke Bay the D'Urville Formation lies with angular unconformity of several degrees on Middle Quaternary and older strata and is truncated, at different places, by each of the three younger wave-planed surfaces (Fig. 2, profile 2). Off Cape Turnagain, beds (Fig. 2, profile 9) that are truncated by W3 are correlated with the D'Urville Formation and are divisible into an upper group and a lower group. The upper group is at its thickest on the upper slope and is considered to represent the period of low sea level immediately preceding the culmination of the Penultimate Glacial Age. The lower group is at its thickest to landward of the upper group and is considered to represent the Penultimate Interglacial Age. It follows that the wave-planed surface W4, which is recorded only in Hawke Bay, was eroded during the preceding Antepenultimate Glacial Age.

At the southern end of the Lachlan Depression the D'Urville Formation is $1\frac{1}{2}$ times as thick as the combined thickness of the Cook and the Britomart Formation. Making the same assumptions as before, the D'Urville Formation represents ($1\frac{1}{2}$ x 120) = 180 kyr. The underlying W4 was, therefore, formed 180kyr before the 140kyr old W3, that is, about 320kyr ago. In deep sea cores the antepenultimate cold period has been dated at about 330kyr old by Arrhenius (1952) and Ericson <u>et al</u> (1964). Hough (1953) also found evidence of a cold period at 330kyr which is antepenultimate if his cool period at 150kyr is given equal status. Evernden <u>et al</u> (1957) **have** dated the Main Rhine Terrace, correlated with the antepenultimate Mindel Glaciation in the Alps, as 360kyr old. Thus the estimated age of 320kyr for W4 is reasonable.

In New Zealand the Terangian Stage includes deposits of the penultimate interglacial in the Wanganui District (Fleming 1959). Thus the lower part of the D'Urville Formation is correlated with the Terangian Stage of warming and warmth and the upper part of the D'Urville Formation is correlated with the stage of cooling and cold between the Oturian and Terangian Stages. Because the D'Urville Formation represents about 180kyr the upper part of the D'Urville Formation is best correlated with the long interglacial between the Waimaunga and the Porika Glaciations (Suggate 1961) rather than with the short period between the Waimea Glacial Advance and the Waimaunga Glaciation (Suggate 1965). Thus the Waimaunga Glaciation is correlated with the Riss Glaciation and the Porika with the Mindel as suggested by Gage (1961).

RATES OF DEPOSITION AND RATES OF EROSION

Only the two upper formations, the Acheron Formation and the Britomart Formation, are useful for estimating rates of deposition because they are the only two formations that have not been extensively wave-planed. Using the isopach maps (Fig. 7) and the difference in age between the top and bottom of each formation (Table 1) rates of deposition can be calculated for the upper unit of the Acheron Formation, which is correlated with present high sea level, the lower unit of the Acheron Formation, which is correlated with rising sea level and the Britomart Formation, which is correlated with low sea level (Fig. 8).

During each period deposition has been most rapid along a line that is almost parallel with the shore and whose position corresponds with the position of the thickest part of the units that were mapped. At most times and at most places rate of deposition on the line has ranged from 1.5m/kyr to 3m/kyr. The line has migrated landward; during

FIGURE CAPTION

FIGURE 8

Maps showing rates of deposition in metres per thousand years A. upper part of Acheron Formation (0-8kyr); B. lower part of Acheron Formation (8-20kyr); C. Britomart Formation (20-55kyr). Stippled area represents land A. about 5kyr ago, B. about 10kyr ago, C. about 20kyr ago. Arrows indicate coastal currents that move sediment. Grey lines are depth to top of each formation in metres.

177° 30'
39° 30'
LACHLAN RIDGE
LACHLAN BANKS
Hawke Bay
CAPE KIDNAPPERS
MOTUKURA DEPRESSION
MOTUKURA BANK
MADDEN DEPRESSION
TURNAGAIN BANKS
TURNAGAIN SEA VALLEY
40° 30'
176° 30'
A
B
C
Present land
Strong reflector (Fig. B)
Gently dipping parts of wave - planed surface WI (Fig C)
0
10
20
Kilometres

low sea level it was 20-25km from the present shore and 15-20km from the 20kyr old shore (Fig. 8c), whereas now it is only 5-10km from the present shore (Fig. 8a). The line was deeper during low sea level, being 250-350m below present sea level (measured to the middle of the Britomart Formation) whereas now it is only 50-100m deep (measured to the middle of the upper part of the Acheron Formation). The line is about the same distance from land but much shallower in southern Hawke Bay than on the shelf to the south. During low sea level sediment was probably deposited most rapidly at a depth of about 100m but subsequently sea level has risen, the seabed has been downdropped (Lewis, in press b) and sediment has slumped (Lewis, in press d).

The position of an area where deposition exceeds 3m/kyr has migrated northward, as well as landward from the upper slope 40km south of Cape Kidnappers to the inner shelf 10km south of Cape Kidnappers. It has migrated because the source of most of the sediment has also migrated. During low sea level the mouths of the southern Hawke Bay rivers were about 20-30km seaward of their present position (Fig. 8c) and then, as now, sediment was transported about 50km by a southward flowing coastal current to an area of relatively deep water. Ridgway (1962) showed that at the present time a coastal current flows southwards and eastwards in southern Hawke Bay, and as long ago as 1827 the explorer D'Urville noted muddy water moving southward from Cape Kidnappers. He assumed the muddy water came from southern Hawke Bay rivers which had not then been found by Europeans (Wright 1950).

Using the isopach maps (Fig. 7) it is also possible to calculate the total volume of sediment deposited during high sea level, rising sea level and low sea level on the 180km long section of continental shelf and upper slope that lies between Napier and Castlepoint (Table 2). Using the dates given in Table 1 the average volume of sediment deposited per thousand years can be calculated (Table 2). The apparently faster rate of deposition during the present high sea level may be attributed to the most recent deposits being less compacted than older deposits and to low sea level deposits on the upper slope having slumped and having been

TABLE 2

Volume of sediment deposited on the 180km long section of continental shelf and upper slope between Napier and Castlepoint.

Formation	Volume (in km^3)	Period of Accumulation (in kyr*)	Rate of Deposition (in km^3/kyr)
Upper Acheron	36	8	4.5
Lower Acheron	40	12	3.3
Britomart	130	35	3.7

*kyr = thousand years

NOTE: Rates of deposition are similar during each period.

transported by turbidity currents to the lower slope.

The average volume of sediment deposited on the shelf during the last 8kyr is about 4.5km^3/kyr (Table 3). The volume deposited on the slope during the last 3kyr is estimated from the depth to a dated ash layer (Lewis 1971) to be about 1km^3/kyr. The volume deposited during the last 5kyr on the land that has been reclaimed from the sea is estimated, from a known reclaimed area of 120km (Fig. 8a) and an assumed average thickness of sediment of 2m, to be about 0.05km^3/kyr. Thus, the average amount of sediment being deposited in the area is estimated to be 5.5km^3/kyr.

The amount of sediment that is being deposited may be expressed as weight rather than volume. Clayey silt from fresh cores collected from the study area has a dry weight of 1.25Mg/m^3. Thus the amount of sediment deposited on the coast, shelf and slope between Napier and Castlepoint is about 7 x 10^{9}Mg/kyr or about 7 million tons per year.

Most of the sediment that is deposited in the study area is derived from the land. At most

TABLE 3

Present rates of deposition and present rates of erosion between Napier and Castlepoint.

Rate of Deposition	on coast	0.05km^3/kyr
	on continental shelf	4.5 km^3/kyr
	on continental slope	1.0 km^3/kyr
	Total	5.55km^3/kyr
Rate of Supply	Total	5.55km^3/kyr
	by wave erosion	0.15km^3/kyr
	by rivers and by wind	5.4 km^3/kyr

NOTE: That most of the sediment is supplied by rivers and by wind and is deposited on the continental shelf.

places locally formed constituents such as glauconite and shells are a minor proportion of the sediment (Lewis and Gibb 1970; Lewis, in press a). Some sediment is derived from land by erosion at the shore. The area of the rock platform that has been eroded around the headlands is about 60km^2 (Fig. 8a) and the average thickness of rock that has been removed is assumed to be 20m. Hence, since the sea reached the level of the rock platform about 8kyr ago, wave erosion has supplied sediment to the marine environment at an average rate of 0.15km^3/kyr. It follows that most of the sediment that is being deposited in the study area was carried to the sea by rivers and by the wind (Table 3).

Because the amount of sediment that is being supplied from the land is known it is possible to calculate the rate at which the land is being denuded. Rivers that drain to the coast between Napier and Castlepoint have a catchment of 8700km^2. If they supply all of the sediment to the adjacent seabed then an average of 0.6m/kyr is being eroded from the catchment. Because some sediment is derived from other sources the rate of subaerial erosion is probably close to 0.5m/kyr, which is, less than the estimated rate at which most of the land is rising (Wellman 1967).

SEA LEVEL OSCILLATIONS AND A TILTING SUBSTRATE

At any place changes of either the height of the land surface or the depth of the seabed are controlled by three main factors;

1. eustatic changes of sea level,
2. tectonic uplift and downdrop,
3. erosion and deposition.

At all times erosion occurs at most places above sea level and at shallow depths below sea level; deposition occurs at most places deeper than a few tens of metres but is relatively slow a long way from shore. Thus there are four zones of erosion and deposition which are almost parallel with the shore. They are, from the land to the deep sea, the zone of subaerial erosion, the zone of wave planation, the zone of rapid deposition and the zone of slow deposition. The line between the zone of wave planation and the zone of rapid deposition, is important in stratigraphic studies because it is the line between a landward area that is being eroded and a seaward area that is being buried. Usually the shore line merely separates two zones that are being eroded by different processes, although if deposition of beach sediments is rapid the zone of wave erosion may be absent.

Consider first the four zones of erosion and deposition on a sloping substrate with sea level as the only variable. The lines between the four zones are largely depth controlled and must, therefore, migrate together across the sloping substrate as sea level changes. On several occasions during the Late Quaternary Period sea level has fallen 120m below its present level (Flint 1947; Donne _et al._ 1962). On each occasion the position of each of the four zones migrated seaward and the line between erosion and deposition migrated from the inner part to the outer part of the continental shelf.

Note by C.A.F.
Not if true then
on the zero [illegible]

(Fig. 9). Most of the continental shelf has been alternately eroded and buried with sediment while the land and innermost shelf has always been eroded and the upper slope has always been the site of deposition.

Consider, now, a stable sea level and a tilting substrate. An important line on the tilting substrate is the zero isobase which separates a landward area that is rising from the seaward area that is subsiding. At most places in the study area the zero isobase is on the inner continental shelf close to the line between erosion and deposition. It is not fortuitous that these two important lines are close together; a simple consideration of the geometry will demonstrate that as any substrate is tilted its intercept with any horizontal plane will move closer to the zero isobase. The line between erosion and deposition is at the intercept of the substrate and a plane that is close to sea level. If the line is landward of the zero isobase then uplift of the substrate ensures that it migrates seawards towards the zero isobase. Conversely, if it is seaward of the zero isobase then subsidence

FIGURE CAPTION

FIGURE 9

Diagram showing position of zones of subaereal erosion (stippled), wave planation (wavy lines), rapid deposition (coloured), slow deposition (white) during Late Quaternary Period. Most of the continental shelf has been alternately the site of erosion and deposition, while the innermost shelf and land havebeen continually eroded and the outermost shelf and slope have been continually buried with sediment. A is Acheron Formation, B is Britomart Formation, C is Cook Formation, D is D'Urville Formation, (u) upper, (l) lower.

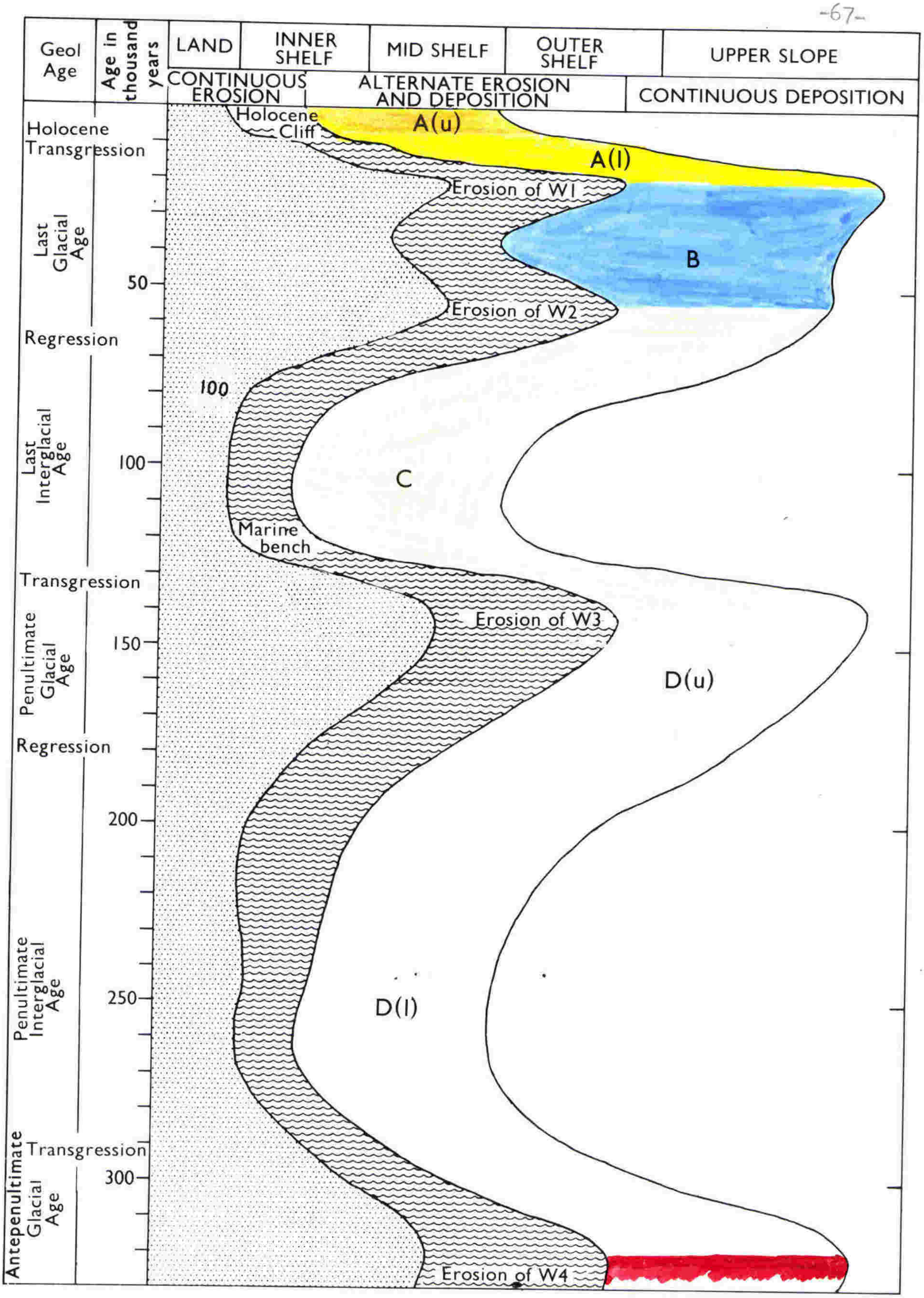

Geol Age
Age in thousand years
LAND
INNER SHELF
MID SHELF
OUTER SHELF
UPPER SLOPE
CONTINUOUS EROSION
ALTERNATE EROSION AND DEPOSITION
CONTINUOUS DEPOSITION
Holocene Transgression
Last Glacial Age
Regression
Last Interglacial Age
Transgression
Penultimate Glacial Age
Regression
Penultimate Interglacial Age
Antepenultimate Glacial Age
Transgression
50
100
150
200
250
300
Holocene Cliff
A(u)
A(l)
Erosion of W1
B
Erosion of W2
100
C
Marine bench
Erosion of W3
D(u)
D(l)
Erosion of W4

Fig. 9

of the substrate ensures that it migrates landwards until it reaches the zero isobase.

Migrations of the four zones when either the sea level remains constant or the slope of the substrate remains constant are relatively simple. The situation is much more complex if both variables are changing simultaneously. In the study area the four zones have migrated during a period of oscillating sea level across a rapidly tilting substrate. The complex stratigraphy and topography produced by migrations to and fro of the four zones is well demonstrated by profiles from near Paoanui Point and near the Porangahau Estuary (Fig. 2, profiles 7, 8). The history of several cycles of migrations is shown by diagrammatic cross sections in Fig. 10.

The last complete cycle of migrations, which was induced by the last complete oscillation of sea level, began about 120kyr ago during the early Last Interglacial Age. At that time the level of the sea and the position of the four zones was about the same as now. While the sea remained at this high level (until about 80kyr ago) the four zones

FIGURE CAPTION

FIGURE 10

Diagrammatic cross sections showing the Late Quaternary history of the continental shelf. They show situation at end of each age. Colours as Figs 2, 3, 4, 9. Shore line and zones of erosion and deposition have migrated to and fro across a seaward tilting substrate in response to eustatic oscillations of sea level. Zero isobase is at red triangle.

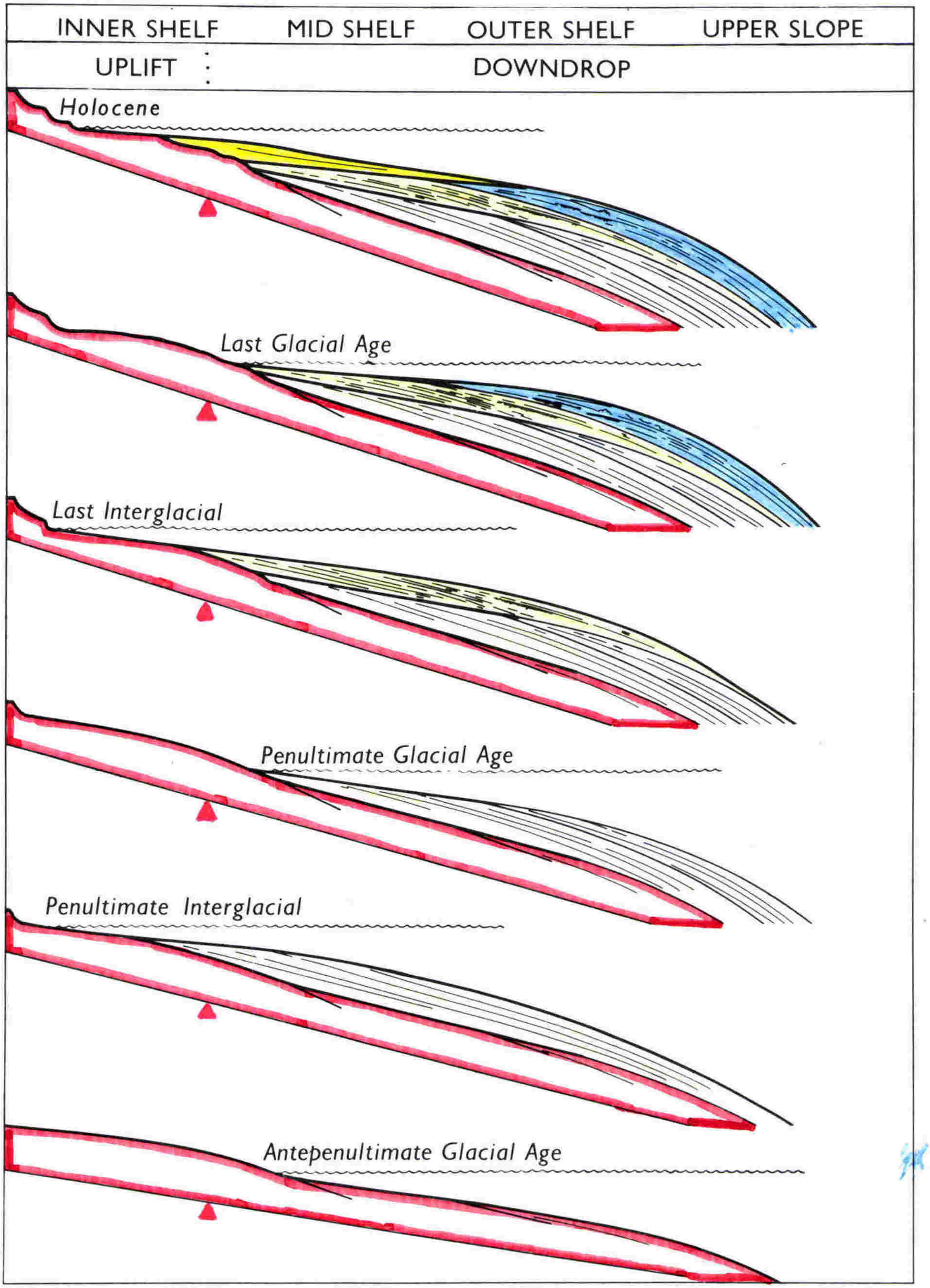

INNER SHELF
MID SHELF
OUTER SHELF
UPPER SLOPE
UPLIFT
DOWNDROP
Holocene
Last Glacial Age
Last Interglacial
Penultimate Glacial Age
Penultimate Interglacial
Antepenultimate Glacial Age

Fig. 10

tended to move to their equilibrium positions on a tilting substrate. At first the line between erosion and deposition was well seaward of the zero isobase because waves eroded only the rocks near the shore and sediment was deposited landward of the zero isobase. Gradually the inner shelf was built up by sedimentation and simultaneously was uplifted so that the line between erosion and deposition moved seaward towards the zero isobase. Thus, erosion and deposition assist movement of the line towards the zero isobase.

About 80kyr ago eustatic sea level began to fall, destroying the equilibrium. The four zones migrated seaward so that waves planed the soft sediments that had been deposited during the Last Interglacial Age and redeposited the upper part of them, together with detritus from rivers, progressively further seaward. Waves also eroded rock and sediment at the Lachlan Ridge so that prisms of sediment were built out from the ridge as well as from the land. Because soft sediment was being eroded the zone of wave planation probably was wide and extended to a relatively great depth below sea level.

[illegible] ? at -120m? Sea level stopped falling about 55kyr ago. A wide zone of wave planation then extended almost to the shelf edge. During the low sea level of Last Glacial Age the zones reached a new equilibrium. As the 55kyr old wave-planed surface subsided it was buried by Last Glacial Age sediments and erosion persisted only on those areas that were rising landward of the zero isobase. Thus the boundary between erosion and deposition had moved to the zero isobase. The volume of sediment reaching the area was more than sufficient to keep pace with the subsidence of the wave-planed surface and most of the sediment continued to be transported to deeper sites on the upper slope and perhaps transported by slumps and turbidity currents to the lower slope.

Towards the end of the Last Glacial Age sea level fell once more and reached a level of about 110m below present sea level about 20kyr ago. At that time the zone of wave planation again extended almost to the shelf break, sediments being eroded to a depth of 50m below the new sea level. Sea level remained low for too short a time for equilibrium to be reached. Sea level then rose rapidly to its present level, and waves began to plane rocks that had been eroded subaerially for a long time. Because hard rocks were being eroded, the zone of wave planation was probably narrow and extended only a few metres below eustatic sea level.

When the sea reached its present level about 7kyr ago the boundary between erosion and deposition began, once more, to migrate seawards towards its equilibrium position. Already at some places on the inner shelf deposition has ceased (Pantin 1966) and erosion may have started.

THE CONTINENTAL SHELF

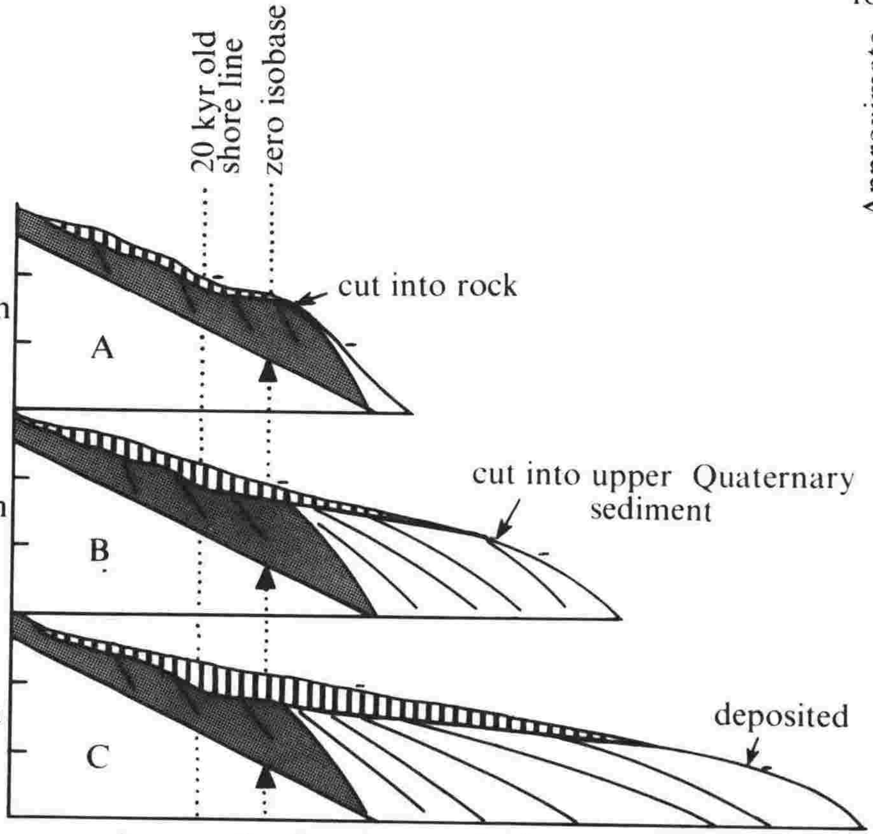
The continental shelf has been formed by erosion of the rising inner shelf and deposition on the subsiding middle and outer shelf during several Late Quaternary oscillations of sea level. The line between nett erosion and nett deposition is at the zero isobase. Wave planation during high sea level has extended the shelf landwards, and deposition during low sea level has extended it seawards. The present topography is largely the result of erosion and deposition during the last 20kyr.

Twenty thousand years ago, a wide, gently sloping platform corresponding to the outer part of W1 and the inner part of W'1 was formed beneath the present middle and outer continental shelf. Most of the platform was cut into soft Late Quaternary sediments but a narrow landward part was cut into older rocks and a narrow seaward part was built out by deposition. To landward of the platform there was a steep erosional surface (the inner part of W1), which was modified by wave-erosion during rising and high sea level. Deposition of the Acheron Formation during rising sea level and high sea level has been most rapid near the change in slope between the steep inner surface and the platform. Therefore, deposition has almost obliterated the topographic expression of the change in slope and produced an almost even gradient from near the shore line to the outer edge of the platform. The change in slope at the outer edge of the platform corresponds to the shelf break.

The depth of the shelf break at most places in the study area is about 200m but off the Porangahau River, where the wave-planed part of the platform ends abruptly at the steep slopes to the Madden Depression, the shelf break is only 160m deep (Table 4). To the south of the study area the continental shelf is narrower and the shelf break is shallower than at the study area. For instance off Kaikoura the shelf break is 120m deep and the steepness of the upper slope suggests that there is no wide platform of Upper Quaternary sediments either because tectonic movements have been rapid (Cotton 1966, 1968) or because little sediment is supplied to the area, or because the sediment that is supplied is transported to the sea along submarine canyons. If there is no platform of Late Quaternary sediments then, 20kyr ago, waves eroded only a narrow platform in hard rocks and the continental shelf is equivalent to only the rising inner part of the continental shelf in the study area. Thus, on the eastern side of New Zealand the depth to the shelf break indicates whether the shelf break is eroded into rock, or eroded into Late Quaternary sediment or built out from an eroded platform. Similar relationships between the depth of the shelf break and the structure of the outer continental shelf may well be found in other parts of the world that are not subject to post-glacial isostatic readjustment.

The shelf break is a relict structure and was formed, in general, at the end of the Last Glacial Age about 20kyr ago but it is an oversimplification to suppose that the shelf break was formed everywhere by wave erosion within 10m of low sea level (Dietz and Menard 1951). At high latitudes glaciers eroded well below low sea level (Uchupi 1966) and off some rivers deltas built out the continental shelf almost at low sea level (Curray and Moore 1964; McMaster et al. 1970). As exemplified by the eastern side of New Zealand waves may erode soft Upper Quaternary sediments to a depth of 50m and the shelf break may be built out by prisms of mud to a depth of 70m below low sea level. Thus, an assumption that variations in the depth of the shelf break are the result of differential

TABLE 4 – Depth and nature of shelf break on eastern side of New Zealand



Depth of shelf break	Profile	Changes since formation 20 kyr ago		Estimated depth of formation
		Approximate tectonic downdrop	Eustatic rise of sea level	
110–130m	A	0 m	110 m	0–20m
130–170m	B	10 m	110 m	20–50m
170–200m	C	20 m	110 m	50–70m

A: south of study area (inferred)
B: off Lachlan Ridge and off Porangahau River
C: Profile 8

deformation (Allen 1963) is not applicable in most areas.

Ancient continental shelves were formed probably to depths of 10-70m after any prolonged period of stable sea level. They were deeper than 70m only after a rapid rise of sea level. An example of an ancient continental shelf that formed under similar conditions to the continental shelf in the study area has been described (Van **Siclen** 1958) from the Permian of the United States. It was shown that sediment facies had migrated to and fro across a seaward tilting substrate. The diagrammatic cross sections of this ancient continental shelf are remarkably similar to the profiles that have formed the raw data of this present study.

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Coloured figures were drafted by Cartographic Section, D.S.I.R.; the rest by Miss P. Lawrence of the N.Z. Oceanographic Institute.

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PAPER 2

GROWTH RATE OF FOLDS USING TILTED WAVE-PLANED SURFACES : COAST AND CONTINENTAL SHELF, HAWKES BAY, NEW ZEALAND.

Accepted for publication in
Collins, B.W. and Fraser, R. (Eds)
"Recent Crustal Movements" Bull. R. Soc. N.Z. 9.

ABSTRACT

On the coast of Hawkes Bay Land District, North Island, New Zealand, tilting and uplift rates are estimated from the dip and the height of the shoreline on the Last Interglacial (120 thousand years old) wave-planed surface. On the continental shelf to the east, wave-planed surfaces show as angular unconformities in continuous seismic profiles. Tilting and downdrop rates are estimated from the differences in dip and in depth between wave-planed surfaces of late Last Glacial age (20 thousand years old) and Penultimate Glacial age (140 thousand years old).

A line, the zero isobase, extends along the inner and middle continental shelf and separates a landward area that is rising from a seaward area that is subsiding.

There are three main growing folds: from west to east, the Kidnappers Anticline, which plunges northeast at its northern end, the Mahia Syncline and the Lachlan Anticline, which both plunge southwest.

Average rates of vertical movement in metres per thousand years are 1.7 for the Kidnappers Anti-

cline where it crosses the coast, 1.5 for the Mahia Syncline where it crosses the edge of the continental shelf and more than 1.6 for the Lachlan Anticline on the eastern side of the Mahia Peninsula.

Average rates of tilting in degrees per thousand years range from 0.002 to 0.023 on the western flank of the Mahia Syncline and from 0.004 to 0.036 on the eastern flank of the Mahia Syncline.

INTRODUCTION

The following account is an attempt to determine rates of tectonic movement for the Late Quaternary from the heights of wave-planed surfaces on the coast and beneath the continental shelf. The area studied is on the eastern side of North Island, New Zealand. It includes the coast of the Mahia Peninsula, the coast from Napier to Cape Turnagain and the adjoining continental shelf out to a depth of about 200m. (Fig. 11 inset).

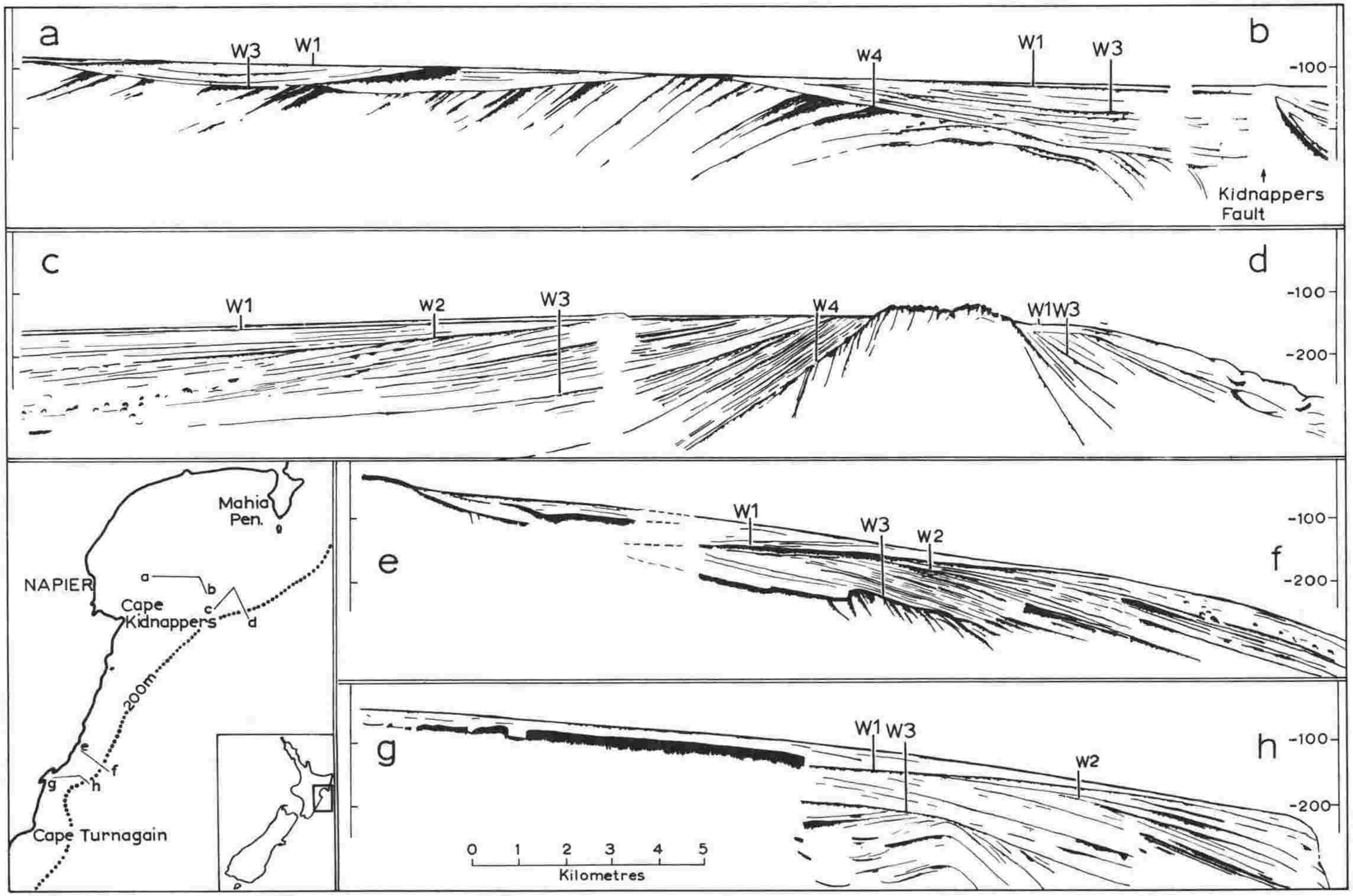
The wave-planed surfaces on the coast are represented by marine benches of Holocene and Last

FIGURE CAPTION

FIGURE 11

Tracings of four selected continuous seismic profiles from the continental shelf off Hawkes Bay Land District, North Island, New Zealand. Wave-planed surface W1 was formed during and since the late Last Glacial low sea level about 20 kyr (thousand years) ago; W2 during an early Last Glacial low sea level about 55 kyr ago; W3 during a Penultimate Glacial low sea level about 140 kyr ago; and W4 during an Anti-penultimate Glacial low sea level. The horizontal scale, in kilometres, is only approximate. The vertical scale is in metres and is exaggerated, relative to the horizontal scale by a factor of about 13. Position of profiles and study area is shown by the inset.

Fig. 11


a
W3
W1
W4
W1
W3
b
-100
Kidnappers Fault
c
W1
W2
W3
W4
W1W3
d
-100
-200
Mahia Pen.
NAPIER
Cape Kidnappers
a
b
c
d
200m
e
f
g
h
Cape Turnagain
e
W1
W3
W2
f
-100
-200
g
W1 W3
W2
h
-100
-200
0 1 2 3 4 5
Kilometres

Interglacial Age (Fig.12). The heights of shore line features were determined on the Holocene benches by levelling to the horizon and on the Last Interglacial benches by using either a Paulin barometer or the heights on existing maps.

The wave-planed surfaces beneath the continental shelf show as angular unconformities in profiles obtained from continuous seismic reflection surveys, (Figs 11, 12). Their depths below sea level were determined from the profiles. Details of the collection and interpretation of the profiles and of the correlation of the wave-planed surfaces is given elsewhere (Lewis, in press a). The equipment used has been described by Barnes (1970).

During the Late Quaternary the growth and melting of the ice caps caused large eustatic changes in the level of the sea. Because the sea level changed, the position of the shore line and the position of an offshore zone of wave erosion migrated to and fro. Migrations of the zone of wave erosion has controlled the formation of the wave-planed surfaces. During interglacial ages conditions were much the same as now; sea level was high and the zone of wave erosion was near the present shore. During glacial ages sea level was low and the zone of wave erosion was many kilometers seaward of its present position.

In many tectonically stable areas, the zone of wave erosion merely migrates to and fro across the shelf and leaves little evidence of the passage of time. It so happens that the area studied is one of strong tectonic activity. Surfaces near the present coast are uplifted and surfaces on the middle and outer continental shelf are downdropped and rapidly buried. Thus some of them are preserved from subsequent erosion. Those that are preserved are sufficiently different in dip and in height to be interpreted. Consequently the passage of time is recorded by uplifted wave-planed surfaces along the coast and downdropped and buried wave-planed surfaces beneath the continental shelf.

WAVE-PLANED SURFACES ON THE COAST

On the coast there are two wave-planed surfaces, one Holocene and the other of Last Interglacial age. Both have been tilted and uplifted (Figs 12, 13, **Plate 1.**)

On the Holocene surface the height of old shore lines is taken as being the height of the old shore

FIGURE CAPTION

FIGURE 12

Diagrammatic cross section of the coast and continental shelf. Vertical scale is in metres above and below present sea level ~~(depths are negative)~~. The wave-planed surface W1 is underlain by horizontal hatching, W3 by vertical hatching. The steep inner parts of W1 and W3, formed during rising or high sea level, are underlain by sparse hatching. The gently dipping outer parts, formed during low eustatic sea level, are underlain by close hatching. On W1, b_0 is the present shore line; b_5 is the 5 kyr old Holocene shore line; b_{20} (at about -100m) the 20 kyr old shore line and d_{20} the 20 kyr old outer limit of wave-planation. On W3, b_{120} is the 120 kyr old (Last Interglacial) shore line and d_{140} the 140 kyr old outer limit of wave-planation. The broken line is the part of W3 eroded by W1. Z is the line of truncation of W3 by W1. The difference in dip and the difference in height between W1 and W3 are the tilting and uplift for about 120 kyr.

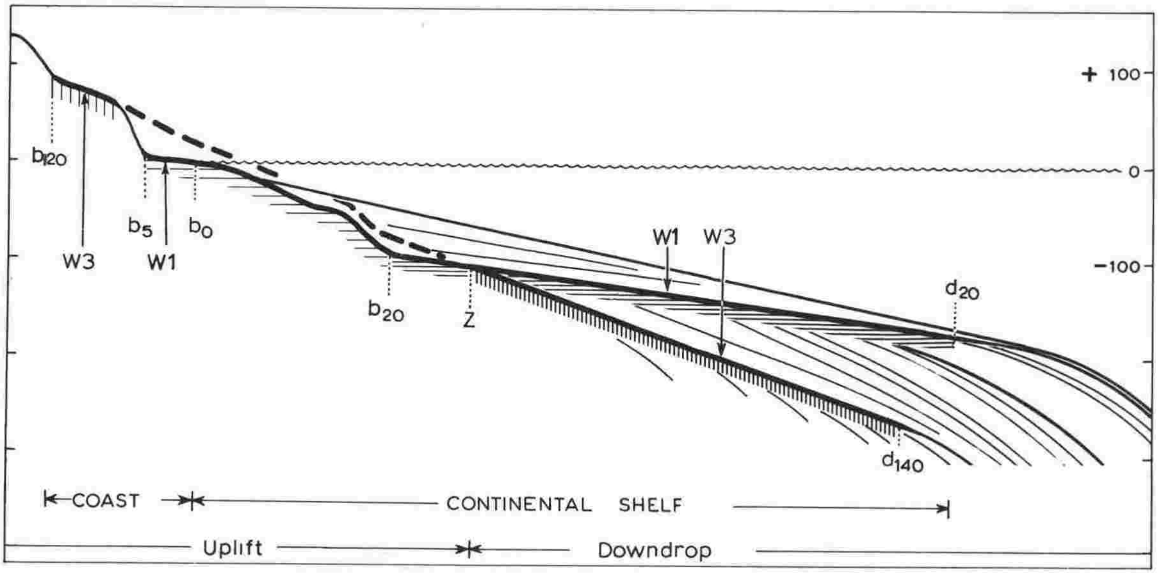

+ 100
0
-100
b120
b5
b0
W3
W1
b20
Z
W1
W3
d20
d140
COAST
CONTINENTAL SHELF
Uplift
Downdrop

Fig. 12

FIGURE CAPTION

FIGURE 13

Map of the coast and continental shelf of Hawkes Bay Land District showing extents of wave-planed surfaces. Height of adjacent land and continental slope in metres. Horizontal hatching represents W1, vertical hatching W3, and cross hatching the area where W1 overlies W3. The steep inner part of W1 (sparse horizontal hatching) extends from the 0, 4, or 5 kyr-old highest Holocene shore line (b_0, b_4 or b_5) to the 20 kyr-old late Last Glacial shore line (b_{20}). The gently dipping outer part of W1 (close horizontal hatching) extends from b_{20} to the 20 kyr-old outer limit of wave-planation (d_{20}). The remnants of the steep inner part of W3 (sparse vertical hatching) are the Last Interglacial marine benches near Cape Kidnappers and at the Mahia Peninsula which have the 120 kyr old shore line (b_{120}) at the inner edge. The remnants of the gently dipping outer part of W3 (close vertical hatching) extend from the line (z) where W3 is truncated by W1 to the 140 kyr-old outer limit of wave-planation (d_{140}).

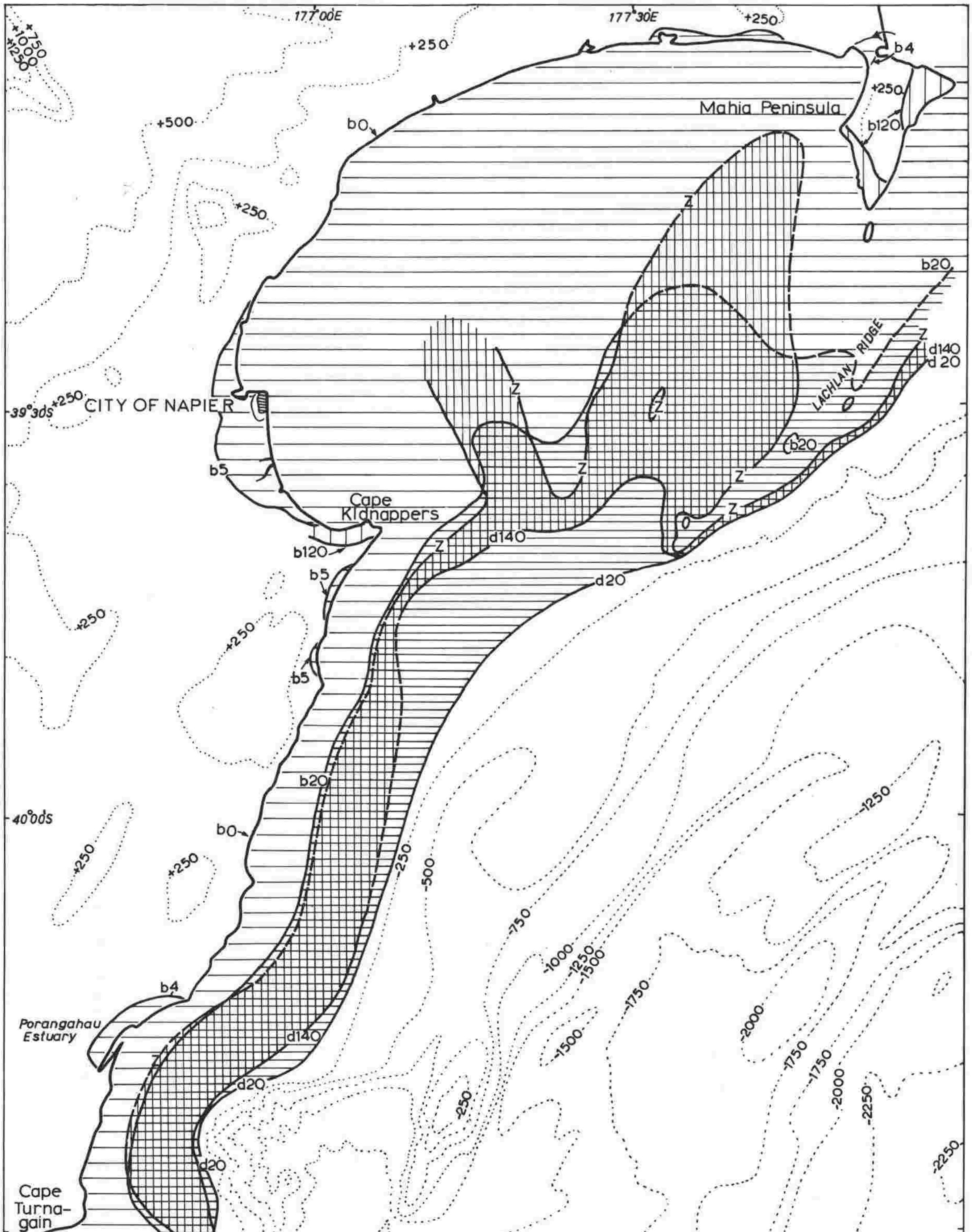

177°00E
177°30E
+750
+1000
+1250
+250
+250
+500
+250
b0
Mahia Peninsula
b4
+250
b120
Z
b20
LACHLAN RIDGE
Z
d140
d20
39°30S
+250
CITY OF NAPIER
Z
Z
Z
b20
Z
Z
b5
Cape Kidnappers
Z
d140
b120
d20
b5
+250
+250
b5
b20
40°00S
b0
-250
-500
+250
+250
-1250
-750
-1000
-1250
-1500
-1750
b4
Porangahau Estuary
d140
-2000
-1500
-1750
-1750
-2000
-2250
d20
-250
d20
-2250
Cape Turnagain
d20
-750
-1750
b20
Z
d140
0
10
20
Kilometres

Fig. 13

PLATE CAPTION

PLATE 1

Oblique aerial photograph of the southern part of Hawke Bay. In the foreground are the Tukituki River and the village of Haumoana; in the background are the cliffs that continue to Cape Kidnappers and the coastal hills. At centre right is a prograding series of Holocene beach ridges. An early Holocene cliff extends from the inner edge of the beach ridges towards the cliffs. Just below the skyline is the Last Interglacial wave-planed surface. The back of the surface is 140m high at left, 210m high in the centre and 100-185m high in the stream dissected area on the right.

features above similar modern shore features (Table 5). The highest shore line is most useful for estimating rates of uplift because the ratio of the uplift to the imperfectly known original height (above present sea level) is highest, and because it can be most easily dated. The age of the highest Holocene shore line in any area can be estimated from its height. To be preserved shore deposits must have remained above eustatic sea level. Thus, since the deposits were formed, local uplift has always exceeded the eustatic rise of sea level. In areas of rapid uplift this occurred so much earlier than in areas of slow uplift. Hence highest shore lines are older and higher in areas of rapid uplift than they are in areas of slow uplift. If the rate of uplift is constant at all localities (but, in general, different at each locality) during the Holocene, then the highest shore lines of the same height are the same age.

The highest shore line at the Porangahau Estuary is about 2m high (Table 5). It is estimated to be 4 kyr* old because it is about the same height as the

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* kyr = thousand years, the basic unit for most geological studies of rates of crustal movement.

TABLE 5 : HEIGHTS OF HOLOCENE AND LAST INTERGLACIAL SHORE LINES

Age	Feature	Position from Cape Kidnappers	Grid Reference	Height above modern equivalents = Height of shore line
Holocene	Highest beach ridge	9km W	44043209	4½m
"	Highest pebbles on beach	5km SW	44633155	5½m*
"	" " "	14km SSW	44143076	6m*
"	" " "	21km SSW	44052979	6m
"	Estuarine mud with *Chione*	80km SSW (Porangahau Estuary)	24144074	(1½ to) 2m
				*cf. King (1933)
Last Inter-glacial	Change of slope at inner edge of marine bench	1½km SW	44843194	140m
"	" " " "	2½km WSW	44743191	160m
"	" " " "	5½km WSW	44403182	210m
"	" " " "	6½km WSW	44313183	185m

highest shore line at the Firth of Thames, near Auckland, which has been radio carbon dated (Schofield 1960) at 4 kyr old. The highest shore lines near Cape Kidnappers are estimated to be about 5 kyr old from plots of shore line heights against age for coasts that have been rising at a constant rate (Wellman 1967, 1969).

When the highest shore deposits were formed, eustatic sea level was probably within 1m of present sea level (Schofield 1960; Wellman 1967, 1969). Thus the heights of the highest shore lines indicate the uplift in the last 4 or 5 kyr, although because of differences in the age of the highest shore line, the relation between height and rate of uplift is not linear.

A wave-planed surface that is assumed here to be of Last Interglacial age is prominent along the south side of Hawke Bay and at Mahia Peninsula, 80km to the north west (Pantin 1963, plates 1, 2). The surface, which ranges from 50 to 210m high and from 0.5 to 3km wide is weathered to about the same extent at each locality. The only younger wave-planed surface is the Holocene one; older wave-planed surfaces are heavily dissected. In many parts of the world, the most prominent (pre-Holocene) marine bench or raised coral reef is of Last Interglacial age and is dated at about 120 kyr; surfaces of this age are found in the Caribbean (Broecker et al. 1968; Veeh 1966), in the Indian and Pacific Oceans (Veeh 1966) and in the Mediterranean (Sterns and Thurber 1965). Thus the prominent wave-planed surface along the south coast of Hawke Bay and at Mahia Peninsula is probably also about 120 kyr old.

The inner edge of the Last Interglacial surface is analogous to the inner edge of the Holocene surface and its height represents the height of the highest Last Interglacial shore line. It probably formed when the rate of eustatic rise of sea level decreased to less than the local rate of uplift at the start of the Last Interglacial Age.

The Last Interglacial wave-planed surface can be identified on N.Z. Lands and Survey Maps (NZMS 2, 1:25,000 series) of the Mahia Peninsula. The highest shore line is lowest in the west, where it is 65m high, and slopes gradually upwards to 140m in the south. It is highest in the east where remnants of the wave-planed surface are 180m high and the highest shore line is estimated to be 200m high. A surface passing through the highest shore line appears to be almost planar and to dip westward.

Along the south coast of Hawke Bay the Last Interglacial wave-planed surface is anticlinally folded. The highest shore line is 140m high near Cape Kidnappers, 210m high 4km to the west and 185m high 1km further to the west (Table 5). An anticlinal axis is inferred to pass through the highest point. The strike and dip of the eastern flank of the anticline can be estimated because the height of the shore line 12km south of Cape Kidnappers can be inferred from the height of a river terrace. The river terrace which was correlated with the marine terrace at Cape Kidnappers by King (1933) and Kingma (in press), is 80m high at the coast. It probably formed close to sea level so that the imaginary surface that passes through the last Interglacial shore line is about 70m high.

WAVE-PLANED SURFACES ON THE CONTINENTAL SHELF

Four wave-planed surfaces are recognised in the seismic profiles (Fig. 11). Their profile to profile correlation and dating is described elsewhere (Lewis, in press). Only two of the surfaces are extensive enough to be useful for determining tectonic rates.

The more steeply dipping and older of the two, W3, is thought to be about 140 kyr old and to correspond to the lowest sea level of the Penultimate Glacial Age. During the rise of sea level to that of the Last Interglacial Age the zone of wave erosion migrated landward, and W3, which is now truncated on the inner continental shelf, is thought to have once connected with the Last Interglacial wave-planed surface on land (Figs 12, 13).

The younger surface, W1, is considered to represent an analogous low sea level of the Last Glacial Age and an analogous rise of sea level to its present level. A wide, almost planar and gently dipping part of W1, which was eroded into Upper Quaternary beds beneath the middle and outer continental shelf, is thought to have formed about 20 kyr ago when the shore line was at its inner edge. As sea level rose the zone of wave erosion migrated landward across a steep surface of much older strata and W1 is continuous with the Holocene wave-planed surface on land.

The other two wave-planed surfaces are W4 and W2; both are seen in only a few profiles. W4, the oldest of the four surfaces, may represent the Antepenultimate Glacial Age. W2 is thought to represent a low sea level of the early part of the Last Glacial Age and to be about 55 kyr old.

TECTONIC RATES FROM WAVE-PLANED SURFACES

Average rates of tilting are estimated from the dip of geological strata as shown on maps and cross-sections. If a 5 Myr old limestone is shown to be dipping at 10° then the average rate of tilting is 2°/Myr.*

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* Myr = million years

Rates of tilting can be estimated from the dip of wave-planed surfaces but the data for the surfaces differs in three main ways from the data for the limestone. First, the dips are so small that an appreciable part is initial dip. Second, each surface is significantly diachronous. Third, seismic profiles and shore lines are not necessarily in the direction of dip, as are the most effective geological cross-sections.

There is no certain way of finding the initial dip of any wave-planed surface and it is certain that the initial dip was, in general, different at different places. It is assumed, however, that the initial dip was much the same at any particular place for all surfaces that formed under similar conditions. Thus on the middle and outer continental shelf the dip of the outer part of W3 is compared with the dip of the almost planar outer part of W1, because each outer part was eroded under similar conditions of low sea level into Late Quaternary strata. On the coast the inner parts of ancient wave-planed surfaces were probably modified during falling sea level, so their dip cannot be compared with the dip of the present inner continental shelf. However, the highest shore line of each ancient wave-planed surface was not modified and was originally horizontal. Therefore its dip is a measure of tilting since its formation.

Although the age of each wave-planed surface is different at different places, at any particular place W3 is about 120 kyr older than W1. The Last Interglacial highest shore line is 120 kyr older than the present shore line; the outer part of W3 is about 120 kyr older than the 20 kyr old outer part of W1. Thus on the continental shelf rates of tilting are estimated not to the present day, as was done for the limestone and the shore lines, but only to the Last Glacial Age.

It follows that contours of the difference in level (relative to present sea level) between W3 and W1 indicate the amount of tilting in 120 kyr (Figs 14, 15,16). The contours on the continental shelf are isopachs of the thickness of sediment between the two surfaces. The direction of tilting is normal to the contours and towards an increasing thickness of sediment. From the distance between contours the average rate of tilting in microdegrees per thousand years

FIGURE CAPTION

FIGURE 14

Map of the coast, continental shelf and continental slope of Hawkes Bay Land District showing axes of growing folds and position of active faults. Fine lines are isobases showing rate of vertical movement in metres per thousand years. The stippled area to landward of the zero isobase is being uplifted, the continental shelf and upper continental slope to seaward of the zero isobase are being downdropped. Dashes across fold axes, faults and isobases indicate position of continuous seismic profiles or observations on land. On the lower continental slope the positions of folds which appear to be growing, are either known from a continuous seismic profile (Houtz _et al_ 1967) or inferred from the bathymetry. Houtz _et al_ (1967) showed that ridges are anticlinal and depressions are synclinal . Also shown are the areas covered in detail by Figs 15 and 16.

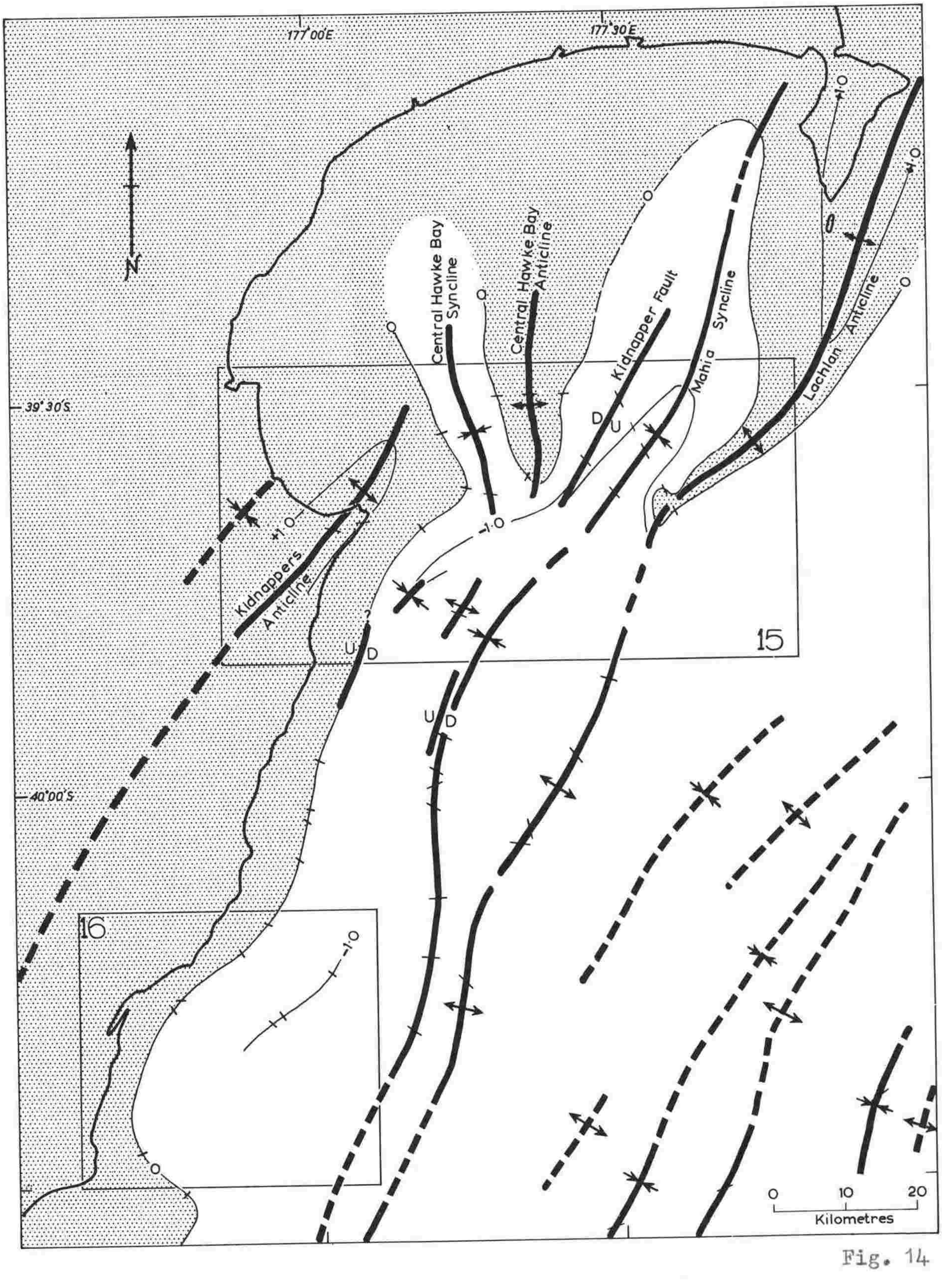
177°00'E
177°30'E
39°30'S
40°00'S
N
Central Hawke Bay Syncline
Central Hawke Bay Anticline
Kidnapper Fault
Mahia Syncline
Lachlan Anticline
Kidnappers Anticline
D
U
U
D
U
D
+1·0
-1·0
0
15
16
0
10
20
Kilometres

Fig. 14

FIGURE CAPTION

FIGURE 15

Map showing isobases at 0.1m/kyr intervals off Cape Kidnappers. Tilt rates in thousandths of a degree per thousand years (equivalent to degrees per million years) can be read off the map with the aid of the tilt scale. The negative isobases are the isopachs of sediment between W3 and W1, i.e. the -0.5, -1.0 and -1.5 isobases equal the 60m, 120m and 180, isopachs. The positive isobases are contours on the surface that passes through the highest Last Interglacial shore line, i.e. the +0.5, +1.0 and +1.5 isobases equal the +60m, +120m and +180m contours. Dashes show the positions of continuous seismic profiles or observations on land. f-f is the Kidnappers Fault.

Fig. 15

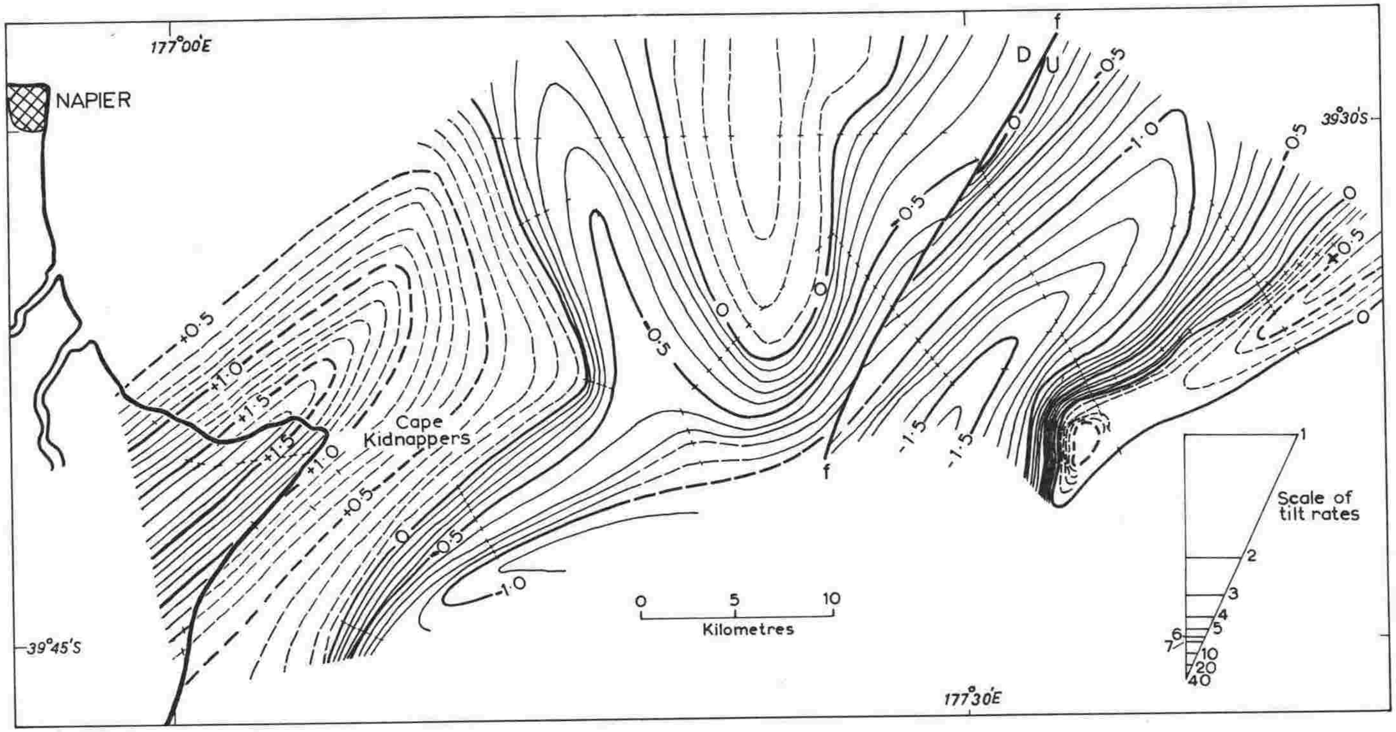
177°00'E
NAPIER
39°30'S
39°45'S
177°30'E
Cape Kidnappers
+0.5
+1.0
+1.5
+1.5
+1.0
+0.5
0
-0.5
-1.0
-0.5
0
0
-0.5
0
-1.0
-1.5
-1.5
-0.5
-0.5
0
+0.5
0
f
f
D
U
0 5 10
Kilometres
Scale of tilt rates
1
2
3
4
5
6
7
10
20
40

FIGURE CAPTION

FIGURE 16

Map, similar to Fig. 15, showing isobases at 0.1m/kyr intervals off the Porangahau Estuary.

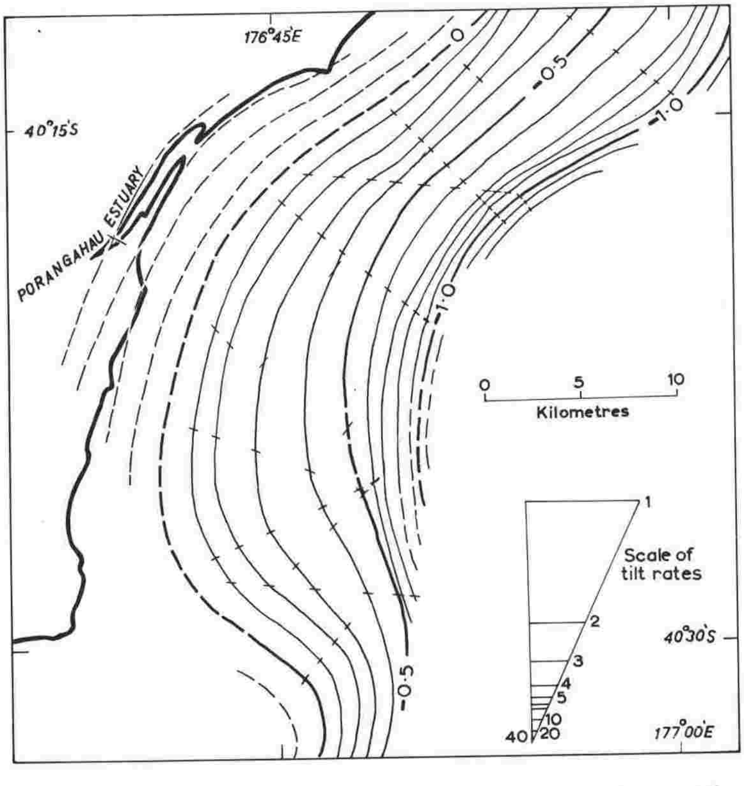
176°45'E
40°15'S
PORANGAHAU ESTUARY
0
-0·5
-1·0
-1·0
-0·5
0
5
10
Kilometres
1
Scale of tilt rates
2
3
4
5
10
20
40
40°30'S
177°00'E

Fig. 16

(^{mo}/kyr), which is numerically equivalent to degrees per million years (^{o}/Myr), can be determined.

Average rates of vertical movement cannot be determined as certainly as can rates of tilting, because some additional information is necessary. If a 5 Myr old limestone is 500m high it is necessary to know, first the depth of formation relative to sea level at the time for formation, and second the sea level at the time of formation relative to present sea level. The first unknown, depth of formation, can often be estimated from fossils. The second unknown, ancient eustatic sea level, is more difficult to determine. Rates of vertical movement can be calculated from the level of wave-planed surfaces relative to present sea level if both depth of formation and ancient eustatic sea levels can be estimated.

On the coast shore lines were formed at sea level and therefore the depth of formation of each shore line is zero. Eustatic sea level, when the Last Interglacial shore line was formed, was probably only a few metres above present sea level (Broecker _et al_ 1968). The difference from present sea level may be negligible because heights of the Last Interglacial shore line were measured only to the nearest 5m. Thus the height of the Last Interglacial shore line is taken as being the uplift in 120 kyr, and rates of vertical movement in metres per thousand years (m/kyr) can be calculated (Figs 14,15).

On the continental shelf W3 formed under similar conditions and in a similar geographical position to W1 (Fig. 13). It is certain that the depth of formation of each surface increased seaward, and it is assumed that at any place each surface formed at a similar depth below sea level. This assumption is implicit in the assumption of similar original dip. The eustatic sea level 20 kyr ago was about 110m below present sea level (Curray 1965). The eustatic sea level 140 kyr ago is unknown, but is assumed to have been the same as 20 kyr ago. It follows that the difference in depth between W3 and W1 is a direct measure of the downdrop in 120 kyr and the rate of vertical movement in metres per thousand years can be calculated. If the assumption of similar eustatic sea level is incorrect a constant must be added to all values for the rate of downdrop, but the distances between contours and, therefore, the values for rate of tilting are not affected. The assumption can be justified if, in a simple tectonic situation, the rates extrapolated landward from the middle continental shelf coincide with rates measured on the coast. At Mahia Peninsula values are not known on the continental shelf. Near Cape Kidnappers the structure is complex. But at the Porangahau Estuary the rate on land agrees well with the rate that would be estimated from the profiles (Fig. 16).

GROWING FOLDS AND ACTIVE FAULTS

On the coast and continental shelf trends of growing folds and active faults are defined by isobase maps (Figs 15, 16). A generalised pattern for the whole area is shown in Fig. 14. The Kidnappers Fault (Pantin 1966) and the three main growing folds, from east to west the Kidnappers Anticline, the Mahia Syncline and the Lachlan Anticline all trend NE-NNE (Figs 14,15). The Central Hawke Bay Anticline and the Central Hawke Bay Syncline trend anomalously N-NNW.

The Mahia Syncline and Lachlan Anticline have been extended to the NNE on each side of the Mahia Peninsula in conformity with the structure defined by the Last Interglacial wave-planed surface. The Kidnappers Anticline and Mahia Syncline have been extended in the same way to the SSW to conform with the structure defined by the profiles.

Rates of vertical movement range from uplift of 1.7 m/kyr for the axis of the Kidnappers Anticline where it crosses the coast to downdrop of 1.5 m/kyr for the axis of the Mahia Syncline where it crosses the shelf edge. The Lachlan Anticline is rising at more than 1.6 m/kyr on the eastern side of the Mahia Peninsula. For the Kidnappers Fault the rate of vertical movement is 0.4 m/kyr. An important point to note (Fig. 14) is that the zero isobase extends along the inner and middle continental shelf and separates a landward area that is rising from a seaward area that is subsiding.

Rates of tilting on the western flank of the Mahia Syncline range from 2^{mo}/kyr off the Porangahau Estuary (Fig. 16) to 23^{mo}/kyr off Cape Kidnappers (Fig. 15). Rates on the eastern flank range from

4^{mo}/kyr on the Mahia Peninsula to 36^{mo}/kyr near the southern end of the Lachlan Ridge. Each of the three main folds is plunging. The axis of the Kidnappers Anticline plunges NE where it crosses the coast. The Mahia Syncline and Lachlan Anticline both plunge SW. The rate of tilting in the direction of the fold axes ranges from about 2^{mo}/kyr to about 5^{mo}/kyr.

Tectonic rates averaged for a period of 120 kyr are not necessarily the same as rates averaged over either longer or shorter periods. Folding and faulting may be limited to infrequent earthquakes (Wellman 1967, 1969). For instance, the earthquake that occurred near Napier in 1931 uplifted, by about 2m, parts of the coast (Henderson 1932) and the seabed (Marshall 1932). Thus rates averaged over a century may be either much more or much less than the rates averaged over several thousand years. However rates measured over several thousand years appear to be similar to those measured over a hundred thousand years. Rates calculated for the 4-5 kyr-old Holocene shore line near Cape Kidnappers are about the same as those calculated for the 120 kyr-old Last Interglacial shore line. The rate of vertical movement for the Kidnappers

Fault is about the same from 20 kyr to present as from 140 kyr to 20 kyr; the rate from 20 kyr to present was calculated from the depth to a conspicuous reflector mapped by Pantin (1966), and here correlated with wave-planed surface W1. At some places tectonic rates during the last 140 kyr were different from rates earlier in the Quaternary. On the western side of the Lachlan Ridge (Fig 11c-d) the zero isobase between W3 and W1 is westward of an earlier zero isobase between W4 and W3 (the position of each zero isobase was obtained by extrapolating the surfaces to their line of intersection). Hence part of the sea-bed moved first downwards and later upwards. The axes of the Central Hawke Bay Anticline and the Kidnappers Anticline are 5-10km westward of an older anticline in supposed Mid-Quaternary and Pliocene strata (Fig 11a-b). The most recent folding has made the earlier anticlines asymmetrical.

On the upper continental slope growing folds are beyond the depth at which wave-planed surfaces have formed so that tectonic rates cannot be measured directly and topography has not been smoothed. Profiles show (Lewis, in press a) that the Mahia

Syncline and Lachlan Anticline continue from the continental shelf of Hawke Bay on to the upper slope south of Hawke Bay, where the Mahia Syncline is defined by a series of depressions and the Lachlan Anticline by a series of ridges. Sediment has been deposited on the growing folds so that dip increases with age just as it does on the continental shelf.

The start of the present regime of folding can be dated by rock samples from the Lachlan Ridge. Ten samples of consolidated mudstone have been dated by their foraminiferal fauna (Lewis, in press b). Eight of the samples - from the southern part of the Lachlan Ridge and ridges to the south - are of either Upper Miocene or Lower Pliocene Age. Two of the samples - from the northern part of the Lachlan Ridge - are of Eocene Age (Pantin 1966). Grains of volcanic ash, glauconite, broken shell and foraminiferal tests are abundant in Late Quaternary sediments from the ridges and other topographic highs on the continental slope (Lewis and Gibb 1970) but are rare in most other Late Quaternary sediments and in the mudstone samples. Thus the mudstones were deposited away from topographic high and before the Lachlan Anticline began to grow. The Lachlan Anticline is, therefore, post-Early Pliocene in age.

Post-Early Pliocene uplift of some of the ridges of the Lachlan Anticline is indicated by the inferred depth at which Miocene and Pliocene benthonic foraminifera lived, being considerably greater than the depth from which they were dredged. However, the direction of vertical movement during the Late Quaternary is unknown.

On the lower continental slope, depressions and ridges correspond to synclines and anticlines (Houtz *et al*. 1967) just as they do on the upper continental slope. Houtz *et al*. (1967) suggested that folding was of ~~the~~ Mid Cretaceous Age, and correlated an unconformity dipping at less than 10° beneath the shelf and upper slope with a Mid Cretaceous unconformity on land. However, on the landward side of the Lachlan Ridge the unconformity corresponds to the Late Quaternary unconformity W4. Post-Early Pliocene tectonic activity has been sufficiently violent on land to be termed the Kaikoura Orogeny and it is well illustrated by uppermost Pliocene limestone having been uplifted to more than 1000m (Kingma 1962) and overturned (Kingma 1958). Folds of similar age are described here from the continental shelf and upper slope. It is therefore reasonable to assume that folds on the lower continental slope are also of post-Early Pliocene age.

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PAPER 3

SLUMPING ON A CONTINENTAL SLOPE INCLINED AT 1° TO 4°.

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ABSTRACT

Continuous seismic profiles from the upper continental slope east of North Island, New Zealand show that surface sediment 10-50m thick has slumped down bedding planes sloping at $1^\circ - 4^\circ$.

There are four slumps, the Kidnappers Slump which has an area of 250sq.km, the Paoanui Slump of 80sq.km, a small slump of only several square kilometres and a slump of undetermined extent. All occurred during the last 20 kyr* in Last Glacial Age sediments. A glide plane is exposed at the head of each slump and beds are thrust or contorted at the toe of some slumps.

Slumping was probably caused by the failure of loosely packed sandy silt during major earthquakes.

INTRODUCTION

Does slumping occur on gentle slopes, on the

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*kyr = thousand years

open continental shelf or continental slope? Fairbridge (1946) presented evidence that it does, which was challenged by Moore (1961) and Boswell (1961). Morgenstern (1967) reviewed the evidence of ancient and modern submarine slumping but gave no unchallenged examples of slumping on open continental slopes inclined at less than 3°.

Evidence of ancient submarine slumps 1-200m thick is seen in many terrestrial exposures in New Zealand. Hills (1940) illustrated convolute folds in Lower Quaternary strata dipping at 1°. Waterhouse and Bradley (1957) suggested that Tertiary beds had slumped on submarine slopes of less than 5° and possibly as low as 1°. Grant-Mackie and Lowry (1964) described Triassic beds which they deduced had slumped after being titled from ½° to 8°.

Slumping of modern submarine beds occurs on steep slopes (Pantin, in press) and in specialised environments such as deltas (Shepard 1955), canyons (Dill 1965; Uchupi 1968) and fjords (Holmsen 1953; Coulter and Migaliaccio 1966). Slumps described from the lower continental slope (Heezen and Drake 1963, 1964; Ross and Shor 1965; Scholl et al 1966;

Uchupi 1967; Roberts and Stride 1968) are thicker than most of the ancient slumps reported from New Zealand but may be analogous to "gravity tectonic" structures described from New Zealand (Stoneley 1968) and other parts of the world (Van Bemmelen 1954; de Sitter 1964).

Evidence from ancient rocks that slumping of soft sediments occurs on gentle slopes in the normal marine environment is supported by continuous seismic profiles from the gently dipping upper continental slope east of North Island, New Zealand.

RECOGNITION OF SLUMPING

Slumping is shown by continuous seismic profiles from off Hawkes Bay Land District, New Zealand (Fig. 17). Profiles were obtained with a sound reflection system based on the 1 kilojoule "Edgerton" thumper as sound source (Barnes 1970). Sound source and hydrophones were towed more than 1000km over the continental shelf and slope between the latitudes of Napier in the north and Cape Turnagain in the south.

FIGURE CAPTION

FIGURE 17

Chart of the area off Hawkes Bay Land District, New Zealand showing position of Kidnappers and Paoanui Slumps and two un-named slumps. Depth in metres from Lewis and Gibb (1970). Cross hatching indicates compressionally folded and thrusted beds at the toes of slumps. Vertical hatching indicates slumped beds that are undeformed or only slightly deformed. Solid black indicates exposed glide plane, usually in zone of tension at the heads of slumps. Large stipples indicate disturbed bedding beneath smooth seabed. Line A-A is the position of the shore during lowered sea level about 20 kyr ago (Lewis, in press a). Line B-B is the edge of the continental shelf.

Inset top left. Map of New Zealand showing locality of study area.

Inset bottom right. Chart showing positions of continuous seismic profiles. Solid black indicates slumps. Numbered profiles are illustrated in Figs 19 and 20.

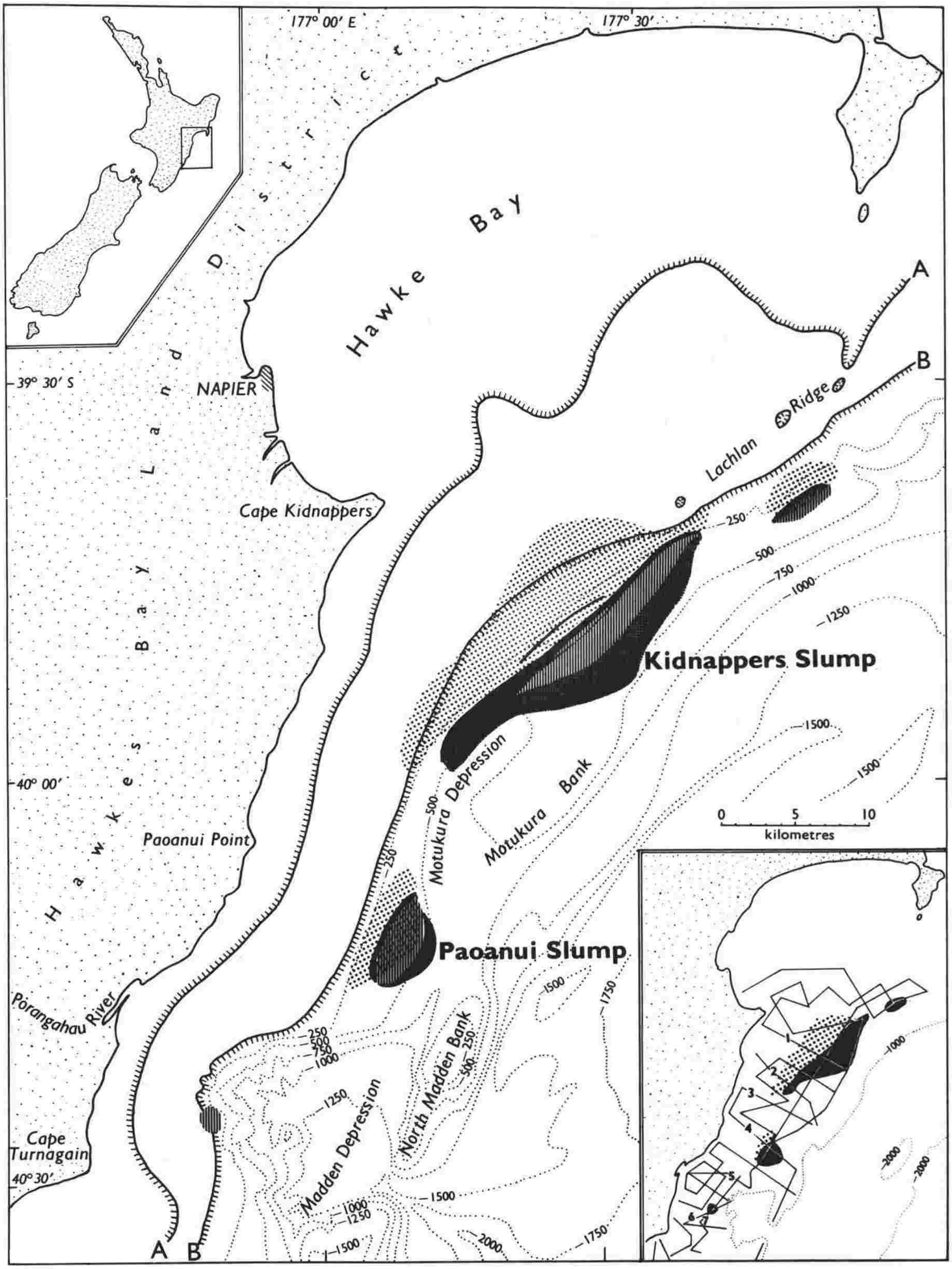

177° 00′ E
177° 30′
Hawke Bay
Hawkes Bay Land District
NAPIER
Cape Kidnappers
39° 30′ S
40° 00′
40° 30′
Paoanui Point
Porangahau River
Cape Turnagain
Lachlan Ridge
Kidnappers Slump
Paoanui Slump
Motukura Depression
Motukura Bank
North Madden Bank
Madden Depression
A
B
250
500
750
1000
1250
1500
1750
2000
0
5
10
kilometres
1
2
3
4
5
6
7

Fig. 17

Some profiles show a smooth seabed and undisturbed subsurface bedding planes. Other profiles show irregular and truncated reflectors which are a result of either wave or current erosion (Lewis, in press a) or a result of slumping.

Slumping is the movement _en masse_ of sedimentary deposits by gravity. A glide plane, which may correspond with a bedding plane for much of its length, separates slumping beds from underlying stable deposits. During slumping there may be compression at the toe of a slump and there must be tension at the head of a slump. Compression raises the seabed by thrusting or folding. Tension lowers the seabed often by faulting which leaves part of a glide plane exposed at the seabed. Slumped beds between zones of tension and compression may be undeformed (Fig. 18).

Compressional structures are recognised as irregularly raised areas of the seabed at the bottom of the upper continental slope off Cape Kidnappers (Fig. 19, profile 1). Reflectors that underlie the irregular surface and dip landward are interpreted as thrust planes. The thrust planes, are oblique to

FIGURE CAPTION

FIGURE 18

Diagrammatic cross section of a slump on a gentle slope. Unstippled beds have slumped; sparsely stippled beds have been disturbed perhaps by intrastratal movement; densely stippled beds have not been disturbed. Cross hatching overlies a zone of compressional folding and thrusting at toe of slump. Vertical hatching overlies a zone of undeformed or slightly deformed beds in the middle of the slump. Solid black overlies an exposed glide plane in a zone of tension at the head of the slump. Large stipples overlie disturbed beds beneath smooth seabed.

Fig. 18

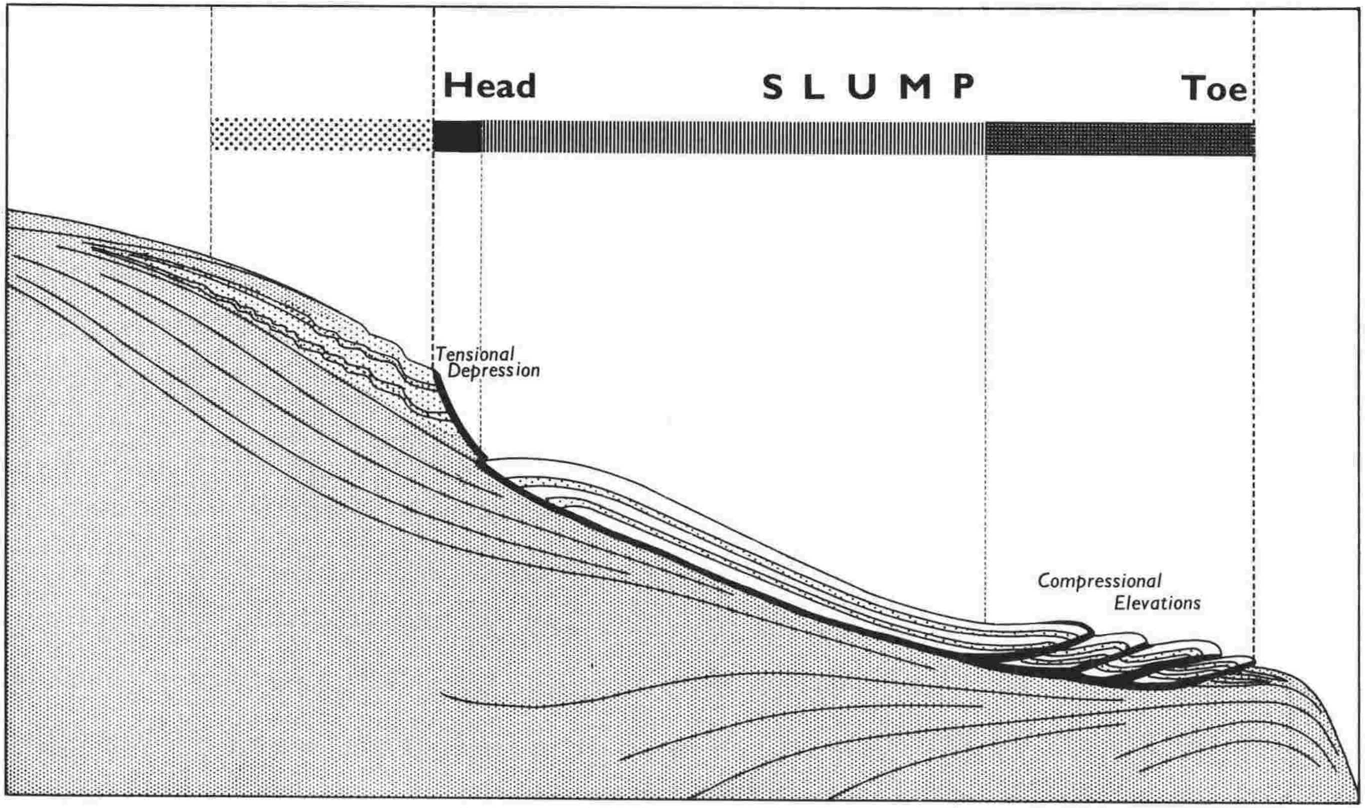

Head
S L U M P
Toe
Tensional Depression
Compressional Elevations

FIGURE CAPTION

FIGURE 19

Tracings of continuous seismic profiles and notable features of each profile. Position of profiles shown in Fig. 17 inset. Unstippled beds have slumped; sparsely stippled beds have been disturbed perhaps by intrastratal movement; densely stippled beds have not been disturbed. Vertical scale in metres assuming the velocity of sound is 1,500m/sec. Horizontal scales in kilometres. Dip scale for profiles 2 and 3 are approximately the same as for profile 1.

Fig. 19

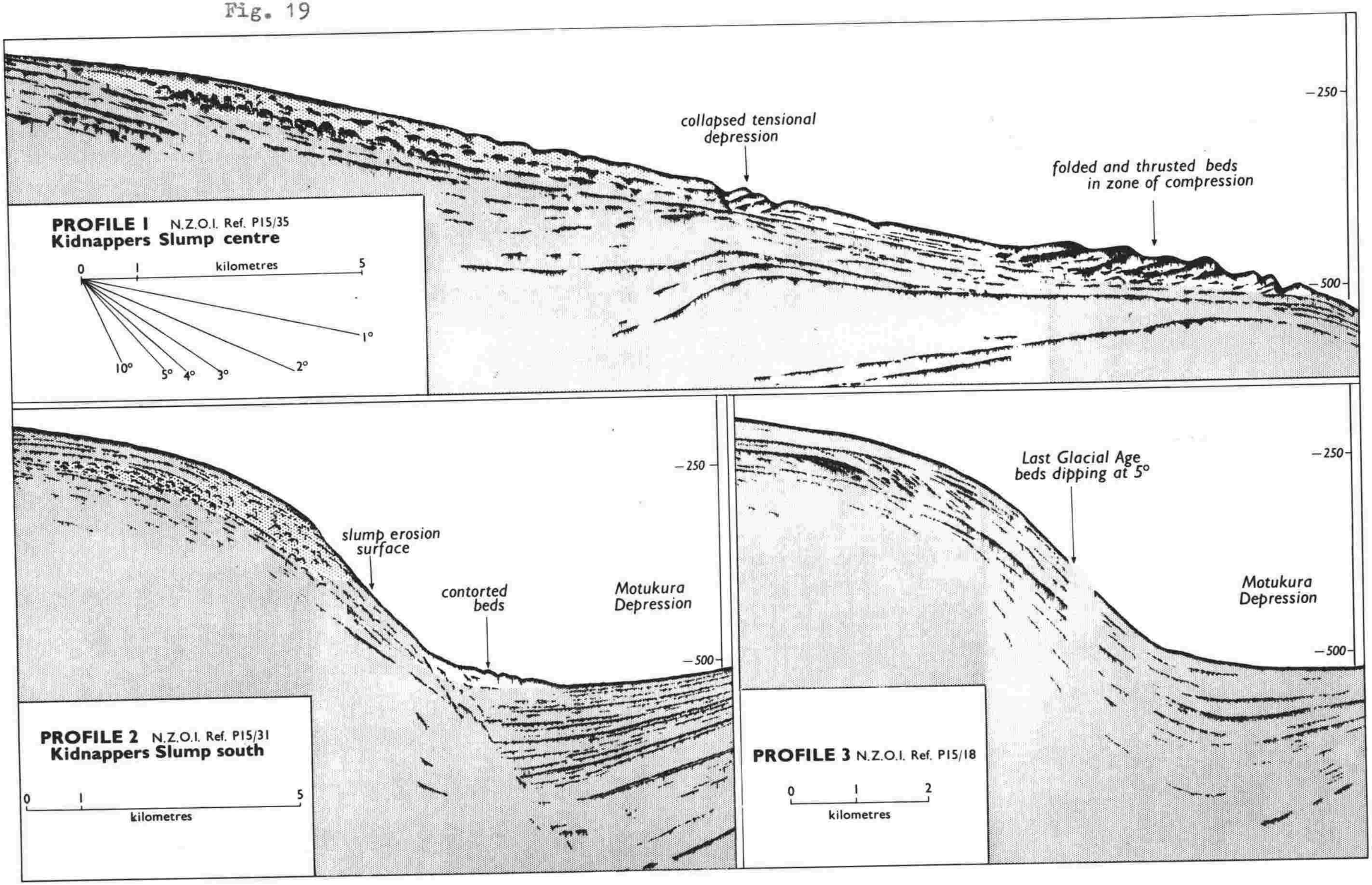
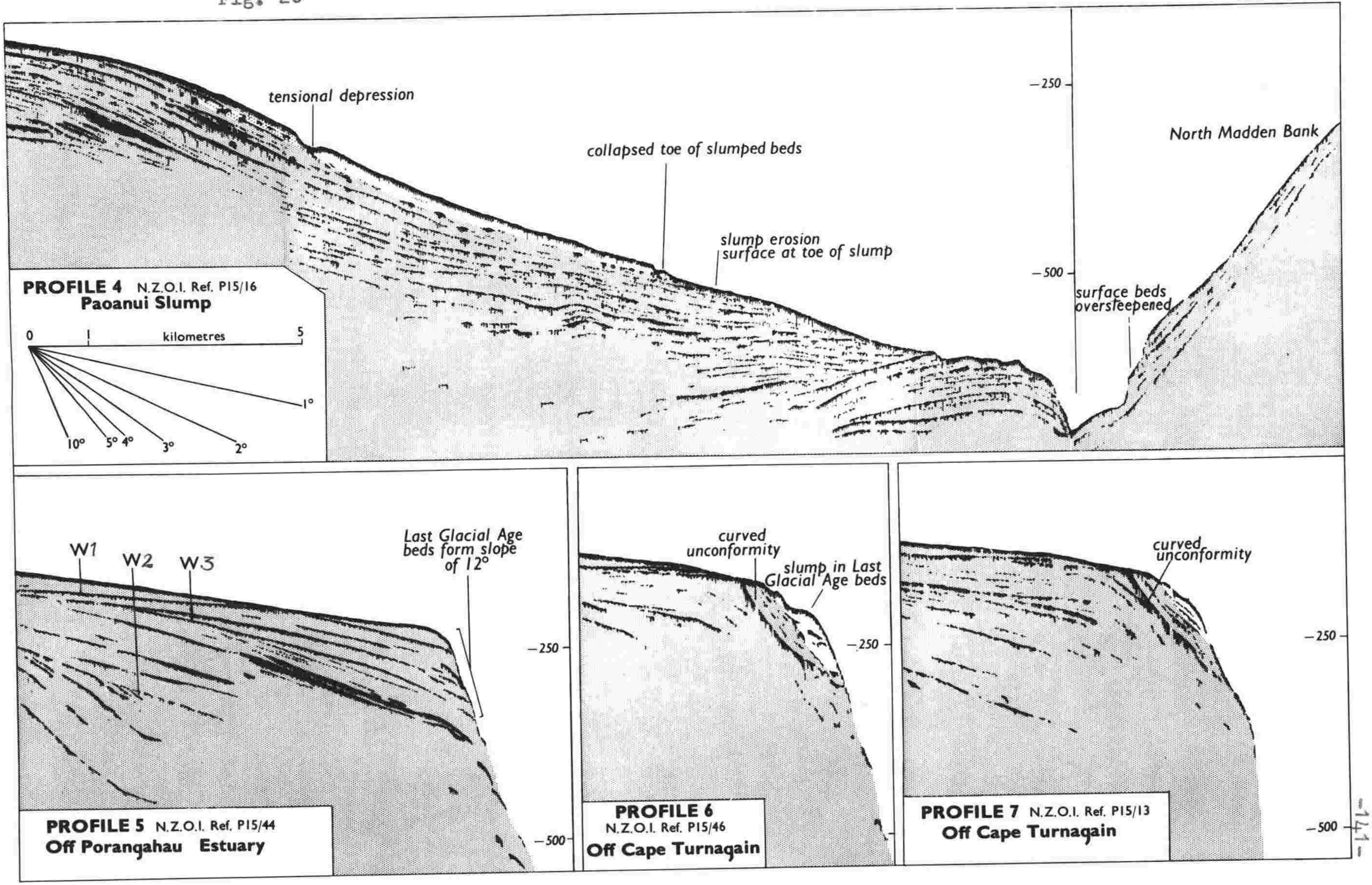

PROFILE 1 N.Z.O.I. Ref. P15/35
Kidnappers Slump centre
0
1
kilometres
5
1°
2°
3°
4°
5°
10°
collapsed tensional depression
folded and thrusted beds in zone of compression
– 250
– 500
PROFILE 2 N.Z.O.I. Ref. P15/31
Kidnappers Slump south
0
1
5
kilometres
slump erosion surface
contorted beds
Motukura Depression
– 250
– 500
PROFILE 3 N.Z.O.I. Ref. P15/18
0
1
2
kilometres
Last Glacial Age beds dipping at 5°
Motukura Depression
– 250
– 500

FIGURE CAPTION

FIGURE 20

Tracings, similar to Fig. 19, of continuous seismic profiles. Horizontal scales and dip scales of profiles 5, 6, 7 are approximately the same as for profile 4. W1, W2 and W3 are unconformities that underlie, respectively, post-Glacial beds, Last Glacial Age beds and Last Interglacial Age beds.

Fig. 20



PROFILE 4 N.Z.O.I. Ref. P15/16
Paoanui Slump

PROFILE 5 N.Z.O.I. Ref. P15/44
Off Porangahau Estuary

PROFILE 6
N.Z.O.I. Ref. P15/46
Off Cape Turnagain

PROFILE 7 N.Z.O.I. Ref. P15/13
Off Cape Turnagain

underlying planar and undisturbed beds.

Tensional structures are recognised as depressions near the top of the continental slope off the Lachlan Ridge, Cape Kidnappers, Paoanui Point and Cape Turnagain. Off Paoanui Point (Fig. 20, profile 4) and the Lachlan Ridge, reflectors that are thought to represent glide planes continue from the upslope side of the depression beneath deposits on the downslope side and merge with a bedding plane 20-40m beneath the seabed. Off Cape Kidnappers (Fig. 19, profile 2) and off Paoanui Point erosion surfaces that are parallel with bedding planes at their lower end and oblique to bedding planes at their upper end are interpreted as the exposed glide planes of slumps which have moved a long distance. The width of exposed glide plane is a measure of the minimum distance that the slumped beds have moved.

Landward of most tensional depressions, bedding planes that lie beneath a smooth seabed are recorded as numerous strongly reflective patches (Fig. 19, profiles 1, 2; Fig. 20, profile 4). The bedding planes may have been deformed by the tension associated with movement of the main slumps and perhaps by intrastratal movement of incompetent beds (Williams 1960, 1963).

The profiles show four slumps, two well-defined slumps which are here named the Kidnappers Slump and the Paoanui Slump, and two other slumps which are not named. The Kidnapper Slump is on the upper continental slope off Cape Kidnappers, the Paoanui Slump is off Paoanui Point and the un-named slumps are off the Lachlan Ridge and Cape Turnagain (Fig. 17). The profiles also show that slumping has not occurred on some comparatively steep slopes.

KIDNAPPERS SLUMP

The Kidnappers Slump involved beds 20-50m thick (Table 6) which moved eastward into the northern part of the Motukura Depression (Fig.17). The slump, including the exposed glide plane at the head, measures a maximum of 11km down the dip of the slope and 45km along the strike of the slope, the total area being about 250sq.km. The area to thickness ratio of the Kidnappers Slump is large compared with most

TABLE 6

Dip and size of major slumps.

	KIDNAPPERS SLUMP			PAOANUI SLUMP
	North	Central	South	
Dip of Glide Plane -				
At head of slump	6.0°		7.0°	6.0°
At top of bedding plane	1.9°	1.2°	3.8°	1.6°
Beneath toe of slump	0.4°	0.4°	0.0°	1.0°
Depth -				
At head	240m	350m	310m	300m
At toe	450m	510m	540m	500m
Thickness -				
Near head	50m?	30m	20m	20m
Near bottom of undeformed slumped beds	25m?	25m		10m
Of contorted beds	40m?	50m	25m	
Glide plane exposed (= minimum distance moved)	0.3km?		2km	0.3km
Dimensions (including exposed glide plane) -				
Down slope	5km	11km	4km	7km
Along slope	45km			
Area	250sq.km			80sq.km
Volume	8cu.km			1cu.km

TABLE 7

Dip and size of deformed beds landward of slumps.

	KIDNAPPERS SLUMP North	KIDNAPPERS SLUMP Central	KIDNAPPERS SLUMP South	PAOANUI SLUMP
Dip of deformed beds	0.4°	1.5°	0.2-3.0°	1.6°
Depth to head of deformed beds	230m	200m	200m	250m
Maximum depth of deformed beds below seabed	50m	50m	60m	30m
Dimension - Down slope	2km	11km	5km	
Along slope		50km		
Area		300sq.km		30sq.km

modern slumps on land. Landward of the slump is an area of about 300sq.km contains minor slumps, and patchy subsurface reflectors (Table 7) which may represent intrastratal deformation.

In the central part of the slump, beds at the toe form a scarp and dip-slope topography. Seven scarps 10-20m high dip seawards at 2 - 6° and dip-slopes dip landward at 0.5 - 2.5°. The dip-slopes are continuations of strong subsurface reflectors which extend down to a glide plane that is parallel to deeper bedding planes (Fig. 19, profile 1). The topography and subsurface reflectors can be attributed to asymmetrical folding and thrusting (Fig. 18). The distance moved along any of the thrust planes is unknown but probably does not exceed a few hundred metres. The tensional depression at the head of the slump has been filled by a small rotational slump from the upslope side of the depression. A similar small rotational slump has been described in ancient strata by Laird (1968).

In the southern part of the Kidnappers Slump, slumped beds form an irregular seafloor in the Motukura Depression (Fig. 19, profile 2). There are no subsurface reflectors within 25m of the seabed probably because beds are too contorted to be resolved by the profiler. A patchy reflector about 25m beneath the irregular seabed is probably the glide plane of the slump and also the original (pre-slump) floor of the Motukura Depression. Immediately beneath the glide plane, beds 10-30m thick are devoid of planar (depression-type) reflectors and may represent older slumped beds or possibly basin sediments deformed by the Kidnappers Slump. On the upper continental slope to landward of the slumped beds there is an erosion surface that is 2km wide. The deeper part of the erosion surface dips at 3.8° and is parallel with bedding planes. The shallower part dips at 4 - 7° and truncates several reflectors. The erosion surface is the exposed glide plane of the beds that now lie in the Motukura Depression. The original seabed, which can be interpolated between the present seabed at the head of the slump and reflectors at the base of the slope, dipped at about 4°. The glide plane is estimated to have been about 20m below the original seabed. The southern part of the Kidnappers Slump moved further and was more deformed than the northern and central parts which occurred on more gentle slopes.

PAOANUI SLUMP

The Paoanui Slump consists of sediments that moved eastward into the southern extremity of the Motukura Depression. It covered a much smaller area than the Kidnappers Slump, the original thickness of sediment was less and consequently the total volume of sediments involved was much less (Table 6).

Note by CAF
that not bevelled
clearly

The toe of the slumped bed is not contorted and beyond the toe a glide plane is exposed at the seabed for several kilometres (Fig. 20, profile 4). Beds that originally covered the exposed glide plane have presumably slumped to the lower continental slope. The slumped beds that remain on the upper continental slope represent only the upper part of the original slump. They show minor rotational slumping at the toe and some disturbance of bedding planes close to the glide plane.

At the head of the slump, a well-defined tensional depression, which is crossed by three profiles, appears in plan view to be concave seawards.

Some bedding planes landward of the slump are strongly reflective in patches perhaps because they have been deformed by intrastratal flow triggered by movement of the slump. Deformed bedding planes that occur beneath the slumped beds may have a similar origin.

OTHER SLUMPS

Seaward of the Lachlan Ridge an irregular topography and irregular subsurface reflectors on a 2^{o} slope are thought to be the result of slumping. As the toe of a slump has not been crossed by a profile, the area of the slump is unknown. The glide plane from the upslope side of a depression merges with a bedding plane 40m beneath the seabed.

Off Cape Turnagain a curved unconformity at the shelf edge (Fig. 20, profiles 6, 7) is either a buried sea-valley or a buried slump erosion surface that was formed by slumping. Within the beds that cover the curved unconformity slumping has occurred along a bedding plane dipping at 4°. The area of the curved unconformity is only several square kilometres.

STABLE SEDIMENTS ON STEEP SLOPES

The continental slope between the Kidnappers and Paoanui Slumps dips at 5°. It is steeper than the glide planes of the major slumps and yet the sediments have remained undisturbed (Fig. 19, profile 3).

Off the Porangahau Estuary, near-surface sediments dipping at less than 1.5° form a "cliff" sloping at 12° but show no evidence of slumping (Fig. 20, profile 5).

On the northern flank of the North Madden Bank surface sediments dipping at 5° have not slumped despite being over-steepened by erosion at the base (Fig. 20, profile 4).

AGE OF SLUMPS

The Kidnappers and Paoanui Slumps occurred in Last Glacial Age beds, which range in age from 20 kyr to 55 kyr old (Lewis, in press a). Thus both slumps are less than 20 kyr old. Sediment deposited on the continental slope during the last 20 kyr is too thin (less than about 3m thick) to appear as a separate layer on the profiles but it may have been involved in the slumps. Thus slumping could have occurred at any time during the last 20 kyr. There is no evidence to show how fast the slumps moved or whether movement occurred at one time or intermittently.

The slump off Cape Turnagain is also in beds of Last Glacial Age and must therefore be less than 20 kyr old. The underlying curved unconformity, which may represent the glide plane of an earlier slump, is of late Last Interglacial Age or early Last Glacial Age because it truncates beds of Last Interglacial Age and is overlain by some undisturbed beds of Last Glacial Age.

CAUSES OF SLUMPING

Slumping occurs in weak sediments on submarine slopes when shear stresses acting downslope exceed the shear strength of the sediment along any potential surface of failure.

A continuous shear stress is exerted by the downslope component of the weight of overlying sediment. The magnitude of the shear stress increases with the slope angle and with the density and thickness of overlying sediment. All of the recognised slumps occurred on the upper continental slope which is the steepest part of the seabed covered by the profiler. Each slump occurred where the bed that failed was most deeply buried by Last Glacial Age beds. The Kidnappers and Paoanui Slumps occurred close to the axis of a growing syncline which was being rapidly filled by sediment built out from the coast (Lewis, in press b). Rates of tilting close to the axis of the syncline on the continental shelf to the north are less than 0.2° in 20 kyr. Thus shear stress can have been increased only slightly by post-depositional tilting. Less than 3m of sediment (less than can be resolved by the profiler) has been deposited on the upper continental slope during the last 20 kyr (Lewis, in press a). Thus shear stress can have been increased only slightly by deposition during the last 20 kyr. It is concluded that the initial depositional slope and the overburden deposited prior to 20 kyr ago were sufficient to cause a relatively large continuous shear stress which has been increased only slightly by tilting and deposition during the last 20 kyr.

An intermittent shear stress is generated by violent earthquakes; Morgenstern (1967) quoted seven examples of major submarine slumps triggered by earthquakes of magnitude greater than 6.5. Several major earthquakes have been recorded from the eastern part of North Island during the last hundred years (Eiby 1968). The most severe, the Napier Earthquake of 1931, had a magnitude of 7.8 and was accompanied by widespread deformation and several major landslides in coastal areas (Marshall 1933). An aftershock of magnitude 7.1 (Eiby 1968) had an epicentre within a few kilometres of the Kidnappers Slump (Adams et al 1933). It is very likely that earthquake-induced shear stresses have triggered slumping off Hawkes Bay Land District.

The shear strength of the sediment opposes slumping. It is a complex function of many parameters including grain size, grain packing, mineralogy, depth of burial, rate of deposition, degree of consolidation and conditions for the escape of pore water at failure.

At each slump, failure occurred mainly along one weak bed which was too deeply buried to be sampled by a piston corer. Thus the physical properties of each weak bed are unknown. Last Glacial Age sediment on the upper continental slope is probably similar to post-glacial sediment on the outer continental shelf - that is, predominantly silt with some sand, clay and volcanic ash (Lewis and Gibb 1970).

A 5.7m long piston core from the outer continental shelf off Cape Kidnappers (NZOI Sta. J61) contained three layers 0.08 - 0.34m thick, of firm clayey fine silt (median diameter 12 microns) and three layers 1.03 - 2.70m thick layers of very soft, water-logged, sandy coarse silt (median diameter 50-60 microns). The clayey silt layers fractured as the core liner was opened - half of each layer adhered to each side of the liner - but the sediment was sufficiently plastic to be moulded easily. The waterlogged sandy silt layers sagged as the core liner was opened and the top of each layer flowed out of the core liner. The sandy silt clearly was much weaker than the clayey silt and, in any similar sequence on the upper continental slope, a sandy silt layer might act as a glide plane.

Sediments rich in coarse silt and very fine sand, frequently have low shear strengths because the grains have little molecular or surface cohesion and often accumulate with a loose, open, metastable packing (Terzaghi 1956; Dott 1963). The collapse of a loosely packed sandy silt by, for instance, earthquake stresses releases pore water, which, being unable to escape rapidly, forms a mobile suspension of silt and sand in water. As few grains are in contact the suspension has almost no shear strength.

A liquified sandy silt layer could permit sliding of an overburden on very low slopes, could produce convolute folds of buried layers (Williams 1960, 1963) and could flow into either tensional fractures or weak parts of the overburden. As excess pore water escapes, the silt and sand grains consolidate in a more densely packed arrangement so that the sediment is stronger than before failure and cannot return to its weaker structure. A layer of densely packed sandy silt consolidated in this way could produce the strong reflections from the thrust planes of the Kidnappers Slump. Similarly strongly reflective patches landward of the Kidnappers and Paoanui Slumps might indicate dense sandy silt in either convolute folds or sedimentary dykes comparable with those seen on the adjacent land (Hills 1941; Waterhouse and Bradley 1957).

Densely packed sandy layers are probably stronger than plastic clayey layers. Slumping might start or continue by either slow plastic deformation of a clayey layer or failure of a thixotropic clayey layer during earthquake stress. A thixotropic sediment loses shear strength each time shear stress is increased - unlike a loosely packed sediment which usually fails only once.

Shear strength usually increases with depth of burial but at any depth in surficial sediments slowly deposited sediments are stronger than rapidly deposited sediments (Moore 1961). The slumps off

Hawkes Bay Land District occurred in the most rapidly deposited Last Glacial Age beds but rates of deposition, which ranged from 1-3m/kyr, were slow when compared with rates of 300m/kyr on the Mississippi Delta (Scruton 1956).

Erosional oversteepening may have reduced the stability of some slopes. At the southern end of the Kidnappers Slump a low angled normal fault runs along the base of the slope (Fig. 19, profile 2). Movement of the fault could have oversteepened the slope and triggered slumping. At the base of the Paoanui Slump sediments have been eroded perhaps by currents funnelled between the North Madden Bank and the continental slope below the slump. Between the Kidnappers and Paoanui Slumps beds that have not failed have not been oversteepened.

In places surface sediments have not slumped even though the slopes have been oversteepened. At one such place on the North Madden Bank lack of slumping may be the result of high shear strength of sediments rich in sand-sized shell, foraminifera and glauconite. The oversteepened Last Glacial Age beds at the Porangahau Estuary have not slumped probably because they are composed of relatively strong muddy sand similar to that which crops out at the shelf break (Lewis and Gibb 1970).

CONCLUSIONS

A. Slumping can occur on normal submarine slopes of only 1°.

B. On the upper continental slope off Hawkes Bay Land District, New Zealand, surface sediment, several tens of metres thick, has slumped on slopes of 1° - 4°. The area of slumps ranges from several square kilometres to hundreds of square kilometres.

C. Slumping was probably caused by the failure of sandy silt during earthquake shock. Slumping occurred where depositional slopes were relatively steep and deposition was most rapid. In places oversteepening by faults or by current erosion may have reduced the stability of slopes.

D. The slump structures seen in continuous seismic profiles from off Hawkes Bay Land District may be comparable with ancient slump structures seen in marine strata exposed on land. The data supports a theory that soft sediments can be deformed by gravitational forces on gentle slopes on the open continental shelf or continental slope.

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PAPER 4

SEDIMENTS ON THE CONTINENTAL SHELF AND SLOPE BETWEEN NAPIER AND CASTLEPOINT

For publication in N.Z. Jl mar. Freshwat Res.

SEDIMENTS ON THE CONTINENTAL SHELF AND SLOPE BETWEEN NAPIER AND CASTLEPOINT

ABSTRACT

Sediments from the seabed off the eastern side of North Island, New Zealand are divided into 12 facies on the basis of grain size and mineralogy of the sand fraction. The facies are grouped into three types; modern detrital sediments, relict detrital sediments and non-detrital sediments. The sediments are described in terms of a modified Wentworth grain size scale and a modified Folk sediment classification.

The modern detrital sediments range from fine sand near the shore to clayey fine silt on the lower slope. At most places they are bi~~o~~modal, probably, because flocs and single grains are deposited together. The relict detrital sediments, which include sands and gravels, occur where deposition is slow on the inner continental shelf and near the shelf edge. Those near the shelf edge include Last Glacial Age sandy muds that have been winnowed and

mixed with Holocene volcanic ash and glauconite. The non-detrital sediments, which contain foraminifera, volcanic ash and glauconite but no detrital sand, occur on anticlinal ridges on the continental slope. At places they overlie muddier sediment deposited during the Last Glacial Age when the sources of river-borne detritus were nearer than at present and mud was deposited more rapidly on the ridges than at present.

INTRODUCTION

The sediments on the continental shelf and slope between Napier and Castlepoint have been charted by Lewis and Gibb (1970). The following account describes the sediment grain size and the sediment mineralogy in more detail and relates them to environment.

The study area lies to the east of a Mesozoic and Tertiary landmass and further to the east and to leeward of the volcanoes of North Island (Fig. 21). A narrow, NNE trending continental shelf reaches a maximum width of 60km off Hawke Bay. The shelf

FIGURE CAPTION

FIGURE 21

Bathymetric chart showing position of sediment samples. Dots show position of analysed samples and circles show position of samples for which only visual descriptions or analyses of sand fractions are available. Depth contours in metres. Broken line marks the edge of the continental shelf at a depth of about 200m.

Inset : Map of New Zealand showing location of bathymetric chart.

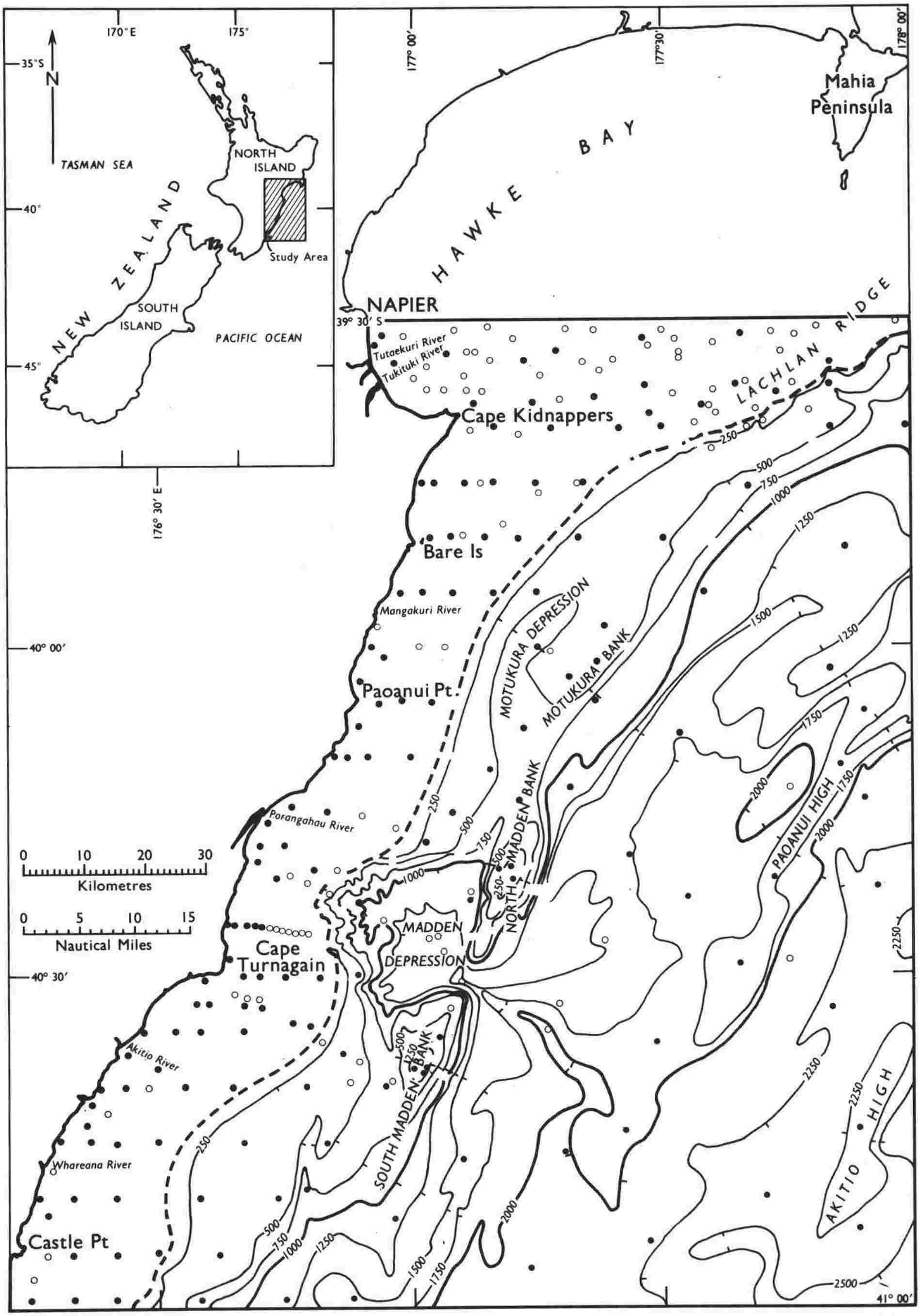

170° E
175°
35°S
N
TASMAN SEA
NORTH ISLAND
NEW ZEALAND
40°
Study Area
SOUTH ISLAND
PACIFIC OCEAN
45°
177° 00'
177°30'
178° 00'
Mahia Peninsula
HAWKE BAY
NAPIER
39° 30' S
Tutaekuri River
Tukituki River
LACHLAN RIDGE
Cape Kidnappers
176° 30' E
Bare Is
Mangakuri River
MOTUKURA DEPRESSION
MOTUKURA BANK
40° 00'
Paoanui Pt.
NORTH MADDEN BANK
PAOANUI HIGH
Porangahau River
0 10 20 30
Kilometres
0 5 10 15
Nautical Miles
MADDEN DEPRESSION
Cape Turnagain
40° 30'
Akitio River
SOUTH MADDEN BANK
Whareana River
AKITIO HIGH
Castle Pt
41° 00'
250
500
750
1000
1250
1500
1750
2000
2250
2500

Fig. 21

break is about 200m deep (Pantin 1963) and the continental slope is folded into a series of anticlinal ridges and synclinal depressions paralleling the continental shelf (Houtz et al 1967; Lewis, in press a). Detrital sediments are transported by southward moving coastal currents and deposited rapidly on the continental shelf and slowly on the continental slope (Lewis, in press b). At places the continental slope sediments have slumped (Lewis, in press c).

Pantin(1966) divided the seabed sediments of Hawke Bay into five types which he related to the effects of waves, rivers and coastal currents. The sediments of the larger area here examined are divided into 12 facies each characteristic of a particular geographic environment. Some of the 12 facies correspond to Pantin's sediment types, others do not.

COLLECTION OF SAMPLES

About 250 sediment samples were collected by the writer with a short gravity corer (Willis 1964) and a segment of each core, between 10mm and about 100mm below the seabed, was retained for sediment analysis; the top was used in another study. The only satisfactory device for collecting sand was an orange-peel grab fitted with protective plates and a canvas bag to prevent sluicing of the surface sediment during recovery. A sample was taken from the surface of each grab haul for sediment analysis.

About 50 samples, collected with a cone dredge, were already available in the N.Z. Oceanographic Institute collection. Those from Hawke Bay have been described by Pantin (1966). Widely spaced data in some parts of the area were usefully supplemented by about 20 brief sediment descriptions noted on the Admiralty Charts.

GRAIN SIZE ANALYSIS

Size analyses were carried out by standard procedures (Van der Linden 1967). The coarse fraction (sand and gravel) being sieved, the fine fraction (silt and clay) being analysed by the pipette method. The sizes of sediment grains are quoted as phi notations (Krumbein 1936) which represent log transformations of sizes in millimetres (McManus 1963).

Each sample was steeped for 12 hours in dilute hydrogen peroxide, then was washed through a 4Ø sieve (mesh diameter 64 µm). The coarse fraction was dried and sieved into ½ phi classes (with a class interval of ½ phi unit) and each class was weighed. The fine fraction was analysed into 1 phi classes down to a minimum size of 7Ø (8 µm) for some samples and 11Ø (0.5 µm) for others. In those samples analysed to 11Ø the cumulative curves between 7Ø and 11Ø are similar to curves produced by assuming an arithmetical decrease in class weights between 7Ø and 14Ø (Fig. 22). Therefore, in all samples the weight of the residue either finer than 7Ø or finer than 11Ø was apportioned into 1 phi classes in such a way that the class weights decreased arithmetically to 14Ø (Fig. 22).

FIGURE CAPTION

FIGURE 22

Plots of cumulative percent against grain-size for 16 samples analysed to 110 (black lines) compared with assumed plots for samples analysed to 70 (white lines). Assumed plots are calculated by dividing the residue finer than 70 into the proportions shown in the histogram A. The residue of samples analysed to 110 is divided in the proportions shown in the histogram B.

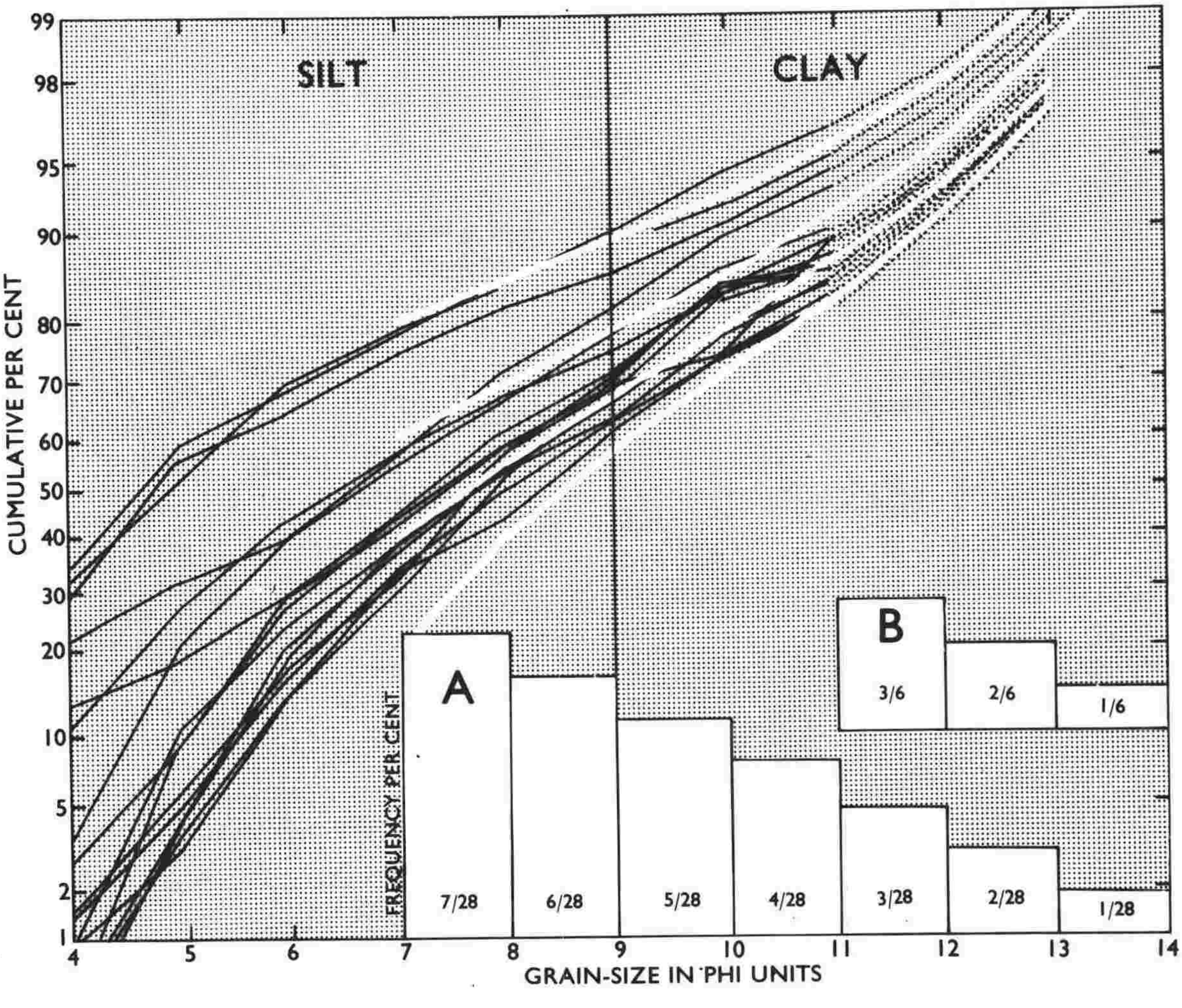

SILT
CLAY
CUMULATIVE PER CENT
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
GRAIN-SIZE IN PHI UNITS
4
5
6
7
8
9
10
11
12
13
14
A
FREQUENCY PER CENT
7/28
6/28
5/28
4/28
3/28
2/28
1/28
B
3/6
2/6
1/6

Fig. 22

GRAIN SIZE NOMENCLATURE AND SEDIMENT CLASSIFICATION

Geologists usually use the grain size nomenclature proposed by Wentworth (1922) which is inconvenient in two respects; the boundary between silt and clay is set unrealistically at 8Ø (4 µm) and the nomenclature of grains coarser than sand is unnecessarily complex.

Geologists have not justified their choice of 8Ø as the silt-clay boundary whereas soil scientists have given cogent reasons for adopting 9Ø as the silt-clay boundary. Indeed, since as long ago as 1936 (Shaw and Alexander 1936; Truog _et al_ 1936) soil scientists have taken 9Ø as the boundary that best separates physically and chemically reactive clays from relatively inert silts. Recently, Grim (1968), a clay mineralogist, noted that naturally occurring clay minerals are rarely larger than 9Ø and non-clay minerals are not usually smaller than 9-10Ø. He concludes "There is, therefore, a fundamental reason for placing the upper limit of the clay size grade at 2 µ [9Ø]". It seems desirable for geologists to modify their grain size nomenclature accordingly and in the following descriptions 90 is taken as the silt-clay boundary instead of Wentworth's 80 (Fig. 23).

Grains coarser than sand are described according to the simplified classification shown in Fig. 23. Wentworth's grade terms granule and cobble were restricted to inconveniently small groups of grains and are therefore abandoned. Granule is included in the pebble size grade and cobbles are included with boulders.

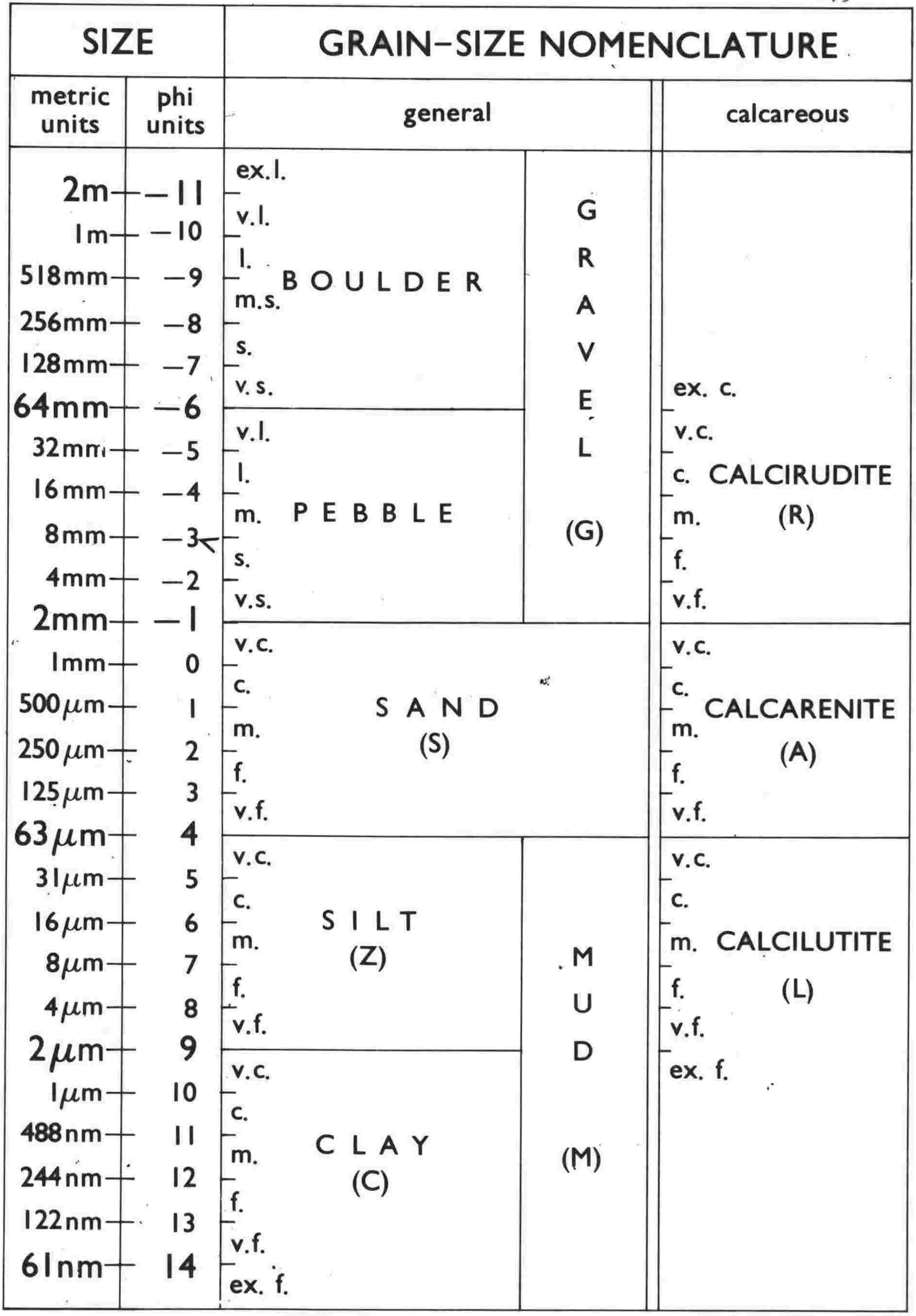
The boulder-pebble boundary and the sand-silt boundary correspond closely to the practical upper and lower limits of sieving. The sand-silt boundary and the silt-clay boundary are close to the practical limits of pipette analysis. The proposed classification has five size grades each of 5 phi classes which can be divided in the same way. Thus it is simple, logical and easy-to-remember and it does conform to normal English usage. It may be used to describe the size of any sedimentary particle or group of particles, e.g. a large pebble sized brachiopod, coarse silt sized magnetite.

Sediments are classified by using the same terms that are applied to grain-size classes.

FIGURE CAPTION

FIGURE 23

Nomenclature for grains of various sizes including nomenclature for carbonate grains. c = coarse; m = medium, f = fine; l = large, s = small; v = very; ex. = extremely.



SIZE		GRAIN-SIZE NOMENCLATURE				
metric units	phi units	general			calcareous	
		ex.l.	BOULDER	GRAVEL (G)		
2m	-11					
		v.l.				
1m	-10					
		l.				
518mm	-9					
		m.s.				
256mm	-8					
		s.				
128mm	-7					
		v.s.			ex. c.	CALCIRUDITE (R)
64mm	-6					
		v.l.	PEBBLE		v.c.	
32mm	-5					
		l.			c.	
16mm	-4					
		m.			m.	
8mm	-3					
		s.			f.	
4mm	-2					
		v.s.			v.f.	
2mm	-1					
		v.c.	SAND (S)		v.c.	CALCARENITE (A)
1mm	0					
		c.			c.	
500µm	1					
		m.			m.	
250µm	2					
		f.			f.	
125µm	3					
		v.f.			v.f.	
63µm	4					
		v.c.	SILT (Z)	MUD (M)	v.c.	CALCILUTITE (L)
31µm	5					
		c.			c.	
16µm	6					
		m.			m.	
8µm	7					
		f.			f.	
4µm	8					
		v.f.			v.f.	
2µm	9					
		v.c.	CLAY (C)		ex. f.	
1µm	10					
		c.				
488nm	11					
		m.				
244nm	12					
		f.				
122nm	13					
		v.f.				
61nm	14					
		ex. f.				

Fig. 23

Most classifications are based on the proportions by weight of gravel, sand, silt and clay in the sediment. The widely used classification of Folk (1954) is employed in this account with slight modification to avoid use of terms "mud" and "muddy" as precisely defined terms (Fig. 24).

REGIONAL TRENDS

A sediment chart (Fig. 25) was constructed by contouring, at Folk's (1954) sediment class boundaries. 1. the percentage of gravel; 2. the percentage of sand in the fraction finer than -1Ø; 3. the percentage of silt in the mud fraction, and 4. the percentage of calcium carbonate in the sand fraction. The spaces between intersecting contour systems indicated by different patterns on the chart, represent different lithologies. In general, the sediment ranges from sand near the shore to clayey silt on the outer continental shelf and continental slope. Patches of coarse sediment occur on some of the offshore ridges.

On the continental shelf the sand fraction

FIGURE CAPTION

FIGURE 24

Diagrams showing sediment classification based on proportions of gravel, sand, silt and clay. (modified from Folk and Ward 1957). Upper case letters as Fig. 23; lower case letters are adjectival equivalents, e.g. g = gravelly, a = calcarenitic. Patterns shown are those used in Fig. 25. In circles are shown patterns and names of sediments occurring in the study area that have more than 50% calcium carbonate in some fraction.

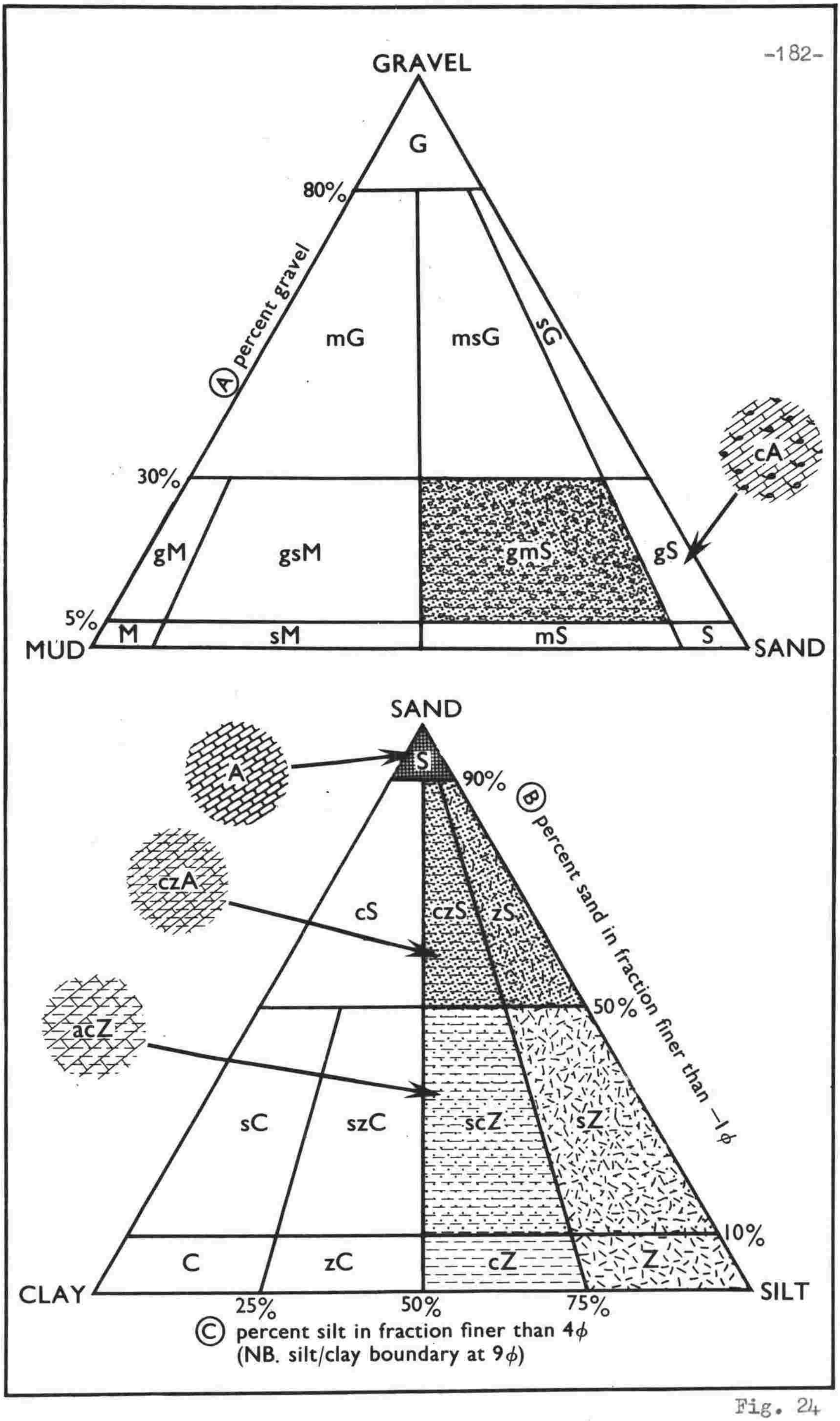

GRAVEL
G
80%
Ⓐ percent gravel
mG
msG
sG
cA
30%
gM
gsM
gmS
gS
5%
M
sM
mS
S
MUD
SAND
SAND
A
S
90%
Ⓑ percent sand in fraction finer than −1ϕ
czA
cS
czS
zS
50%
acZ
sC
szC
scZ
sZ
10%
C
zC
cZ
Z
CLAY
SILT
25%
50%
75%
Ⓒ percent silt in fraction finer than 4ϕ
(NB. silt/clay boundary at 9ϕ)

Fig. 24

FIGURE CAPTION

FIGURE 25

Chart showing distribution of surface sediments according to the classification illustrated in Fig. 4. Broken line is at edge of continental shelf.

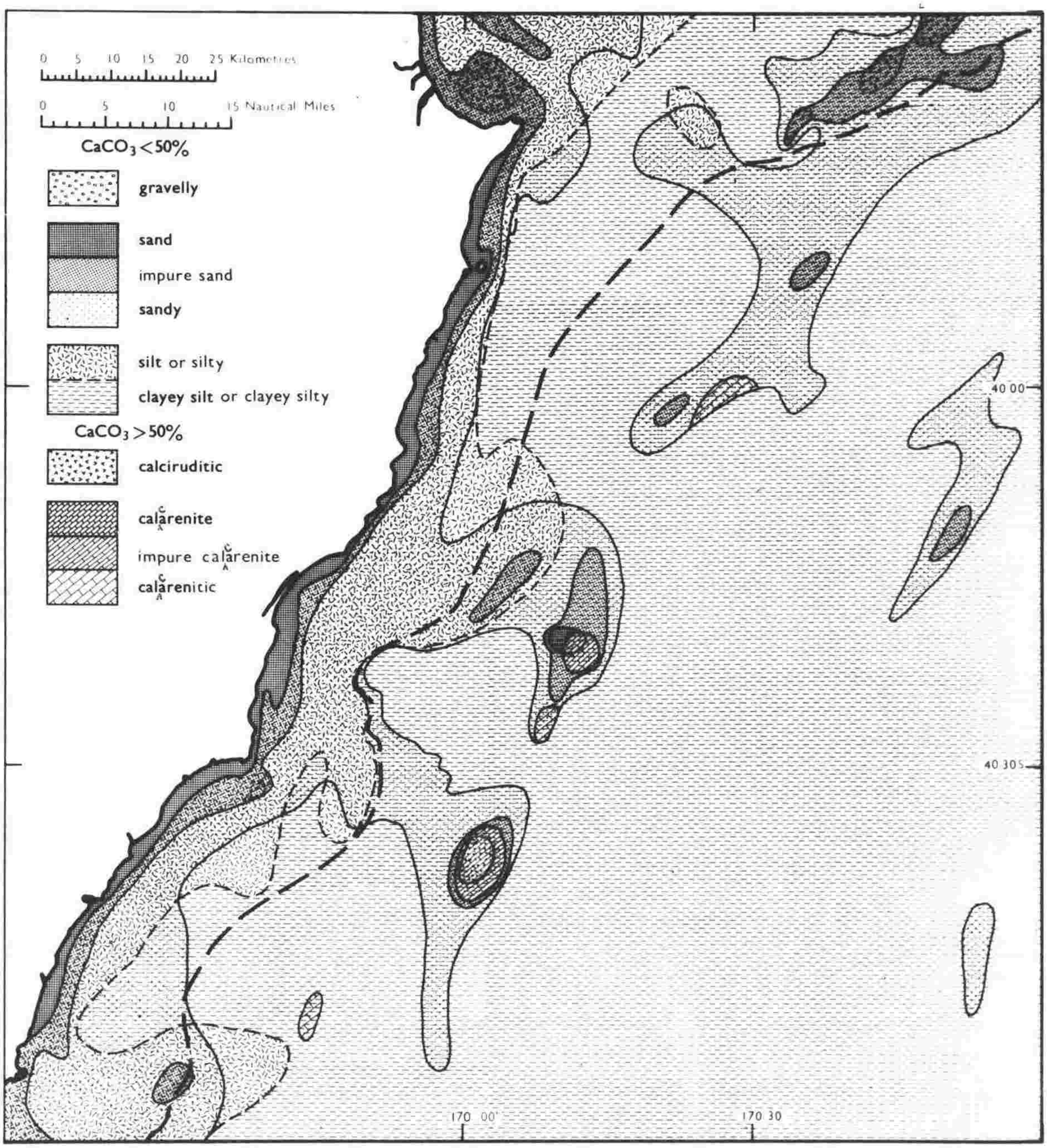

0 5 10 15 20 25 Kilometres
0 5 10 15 Nautical Miles
CaCO3 < 50%
gravelly
sand
impure sand
sandy
silt or silty
clayey silt or clayey silty
CaCO3 > 50%
calciruditic
calcarenite
impure calcarenite
calcarenitic
40 00
40 30S
170 00
170 30

Fig. 25

(Fig. 26) is composed mainly of detrital grains. On the continental slope in the northern part of the area the sand fraction is mainly pumice and unworn volcanic glass. And on the continental slope in the southern part of the area the sand fraction is mainly planktonic foraminifera. Exceptions occur on the continental shelf of central Hawke Bay where volcanic ash predominates and on the offshore banks where the sand fraction includes benthonic foraminifera, comminuted shells and coral debris.

The facies chart (Fig. 27) shows the main sediment types grouped according to grain size and mineralogy of the sand fraction. Some anomalously coarse sediments on the continental shelf and upper slope have predominantly detrital sand fractions; others on the continental slope ridges have a predominantly non-detrital sand fraction.

The percentage of clay in the sediments ranges from zero near the shore to almost 40% on the lower continental slope but the mineralogy of the clay fraction shows no obvious trends (Fig. 28). The proportions of clay minerals in samples from the upper slope ridges were given by Seed (1968). The other samples were analysed by Dr G.G. Claridge,

FIGURE CAPTION

FIGURE 26

Chart showing mineralogical composition of sand fraction by weight. It includes data from Hawke Bay by Pantin (1967). Broken line is at edge of continental shelf. Contours at 75%, 50% and 25% detrital grains and 50% carbonate.

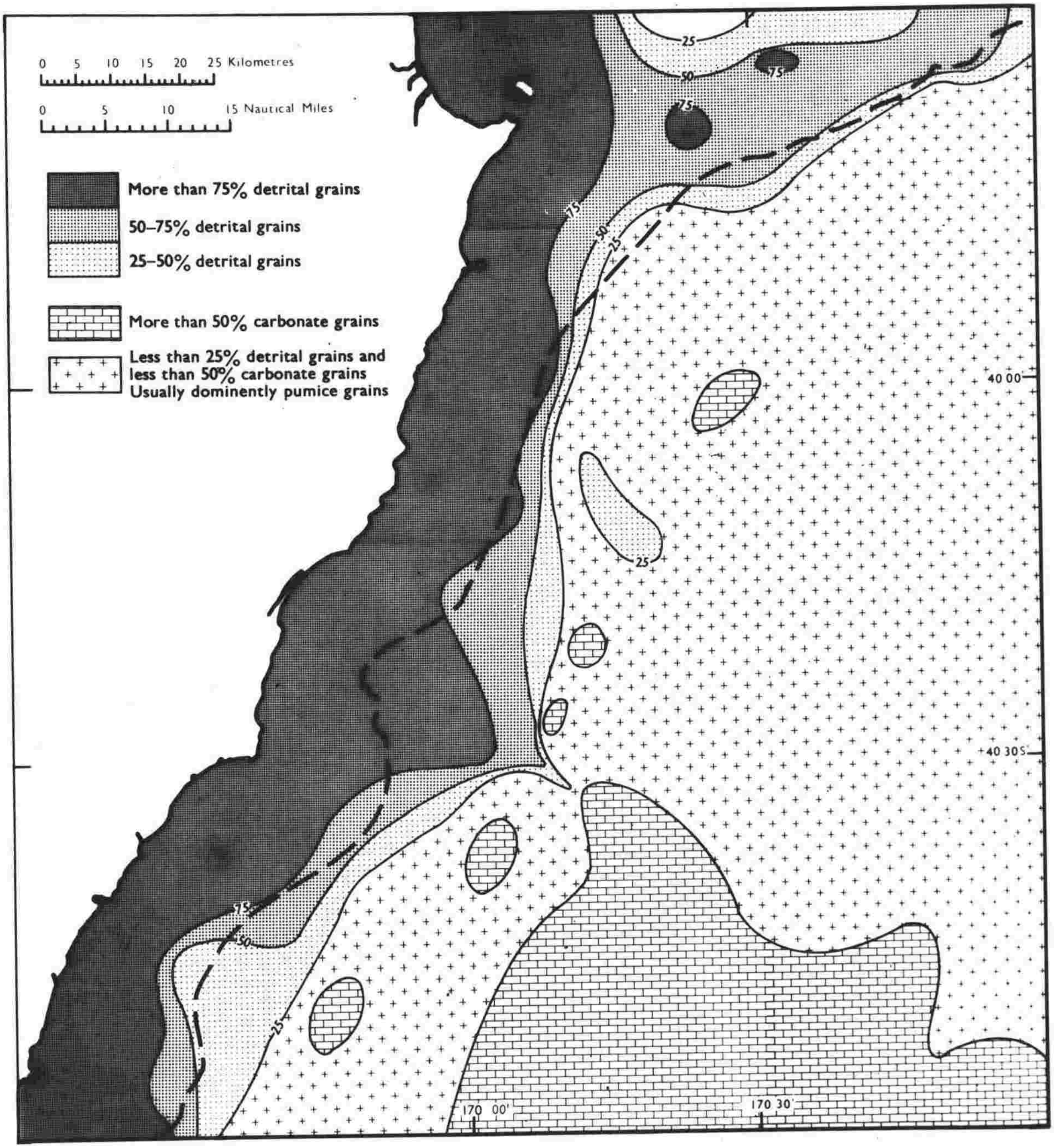

0 5 10 15 20 25 Kilometres
0 5 10 15 Nautical Miles
More than 75% detrital grains
50–75% detrital grains
25–50% detrital grains
More than 50% carbonate grains
Less than 25% detrital grains and less than 50% carbonate grains Usually dominently pumice grains
25
50
75
40 00
40 30 S
170 00'
170 30'

Fig. 26

FIGURE CAPTION

FIGURE 27

Chart showing distribution of main facies. Broken line is at edge of continental shelf.

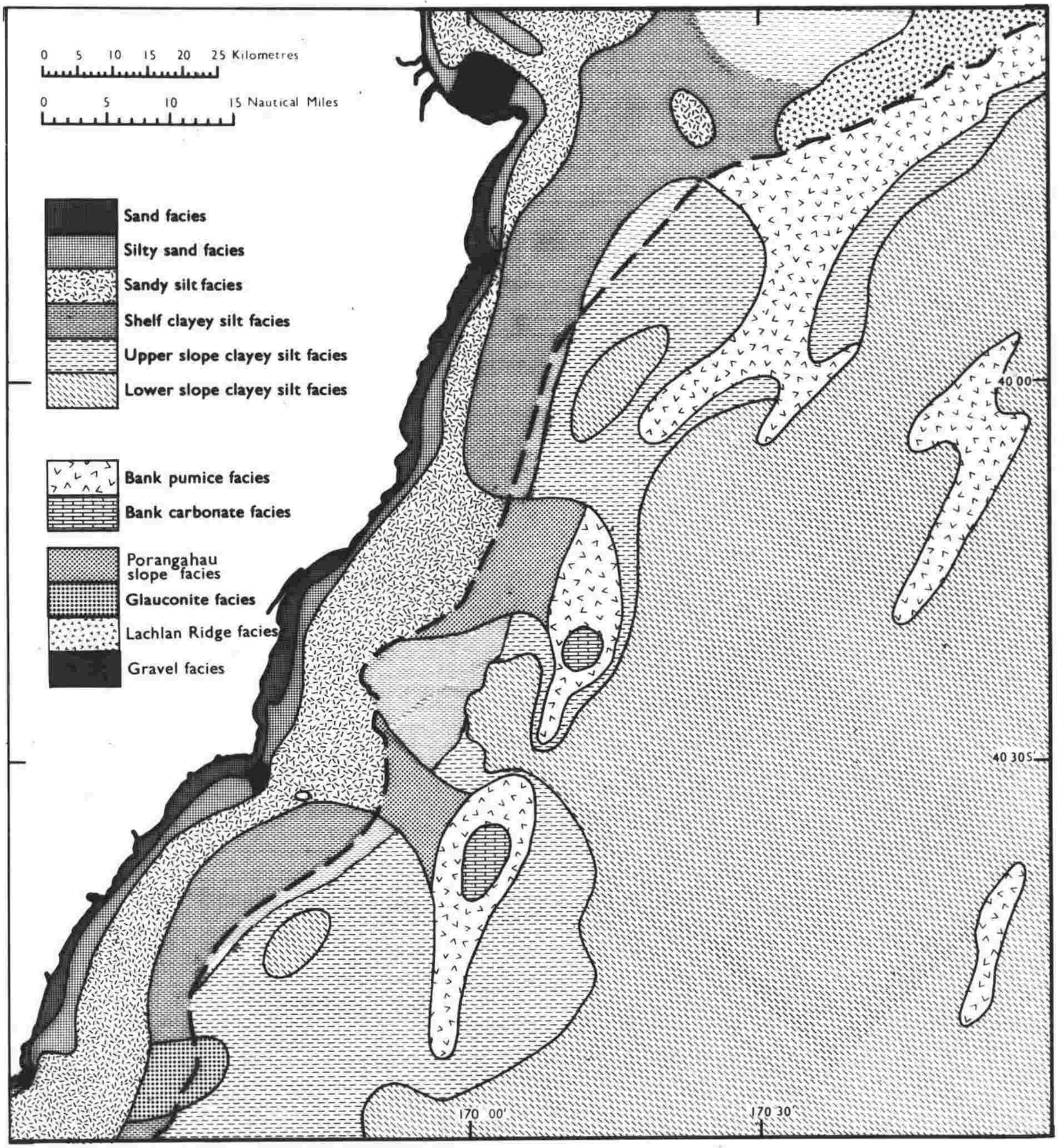

0 5 10 15 20 25 Kilometres
0 5 10 15 Nautical Miles
Sand facies
Silty sand facies
Sandy silt facies
Shelf clayey silt facies
Upper slope clayey silt facies
Lower slope clayey silt facies
Bank pumice facies
Bank carbonate facies
Porangahau slope facies
Glauconite facies
Lachlan Ridge facies
Gravel facies
40 00
40 30S
170 00'
170 30

Fig. 27

FIGURE CAPTION

FIGURE 28

Chart showing percentage of clay sized grains (finer than 90) and results of 14 clay mineral analyses by G.G. Claridge, Soil Bureau, D.S.I.R. (pers. comm.) and four clay mineral analyses by Seed (1968). Dots show positions of analysed samples. Above each dot is the percentage of illite (on the left) and montmorillonite (on the right). Below each dot is either the percentage of chlorite and vermiculit~~r~~e (analysed by G.G. Claridge) or in a bracket the combined percentage of chlorite and vermiculite (analysed by Seed (1968)). Broken line is at the edge of the continental shelf.

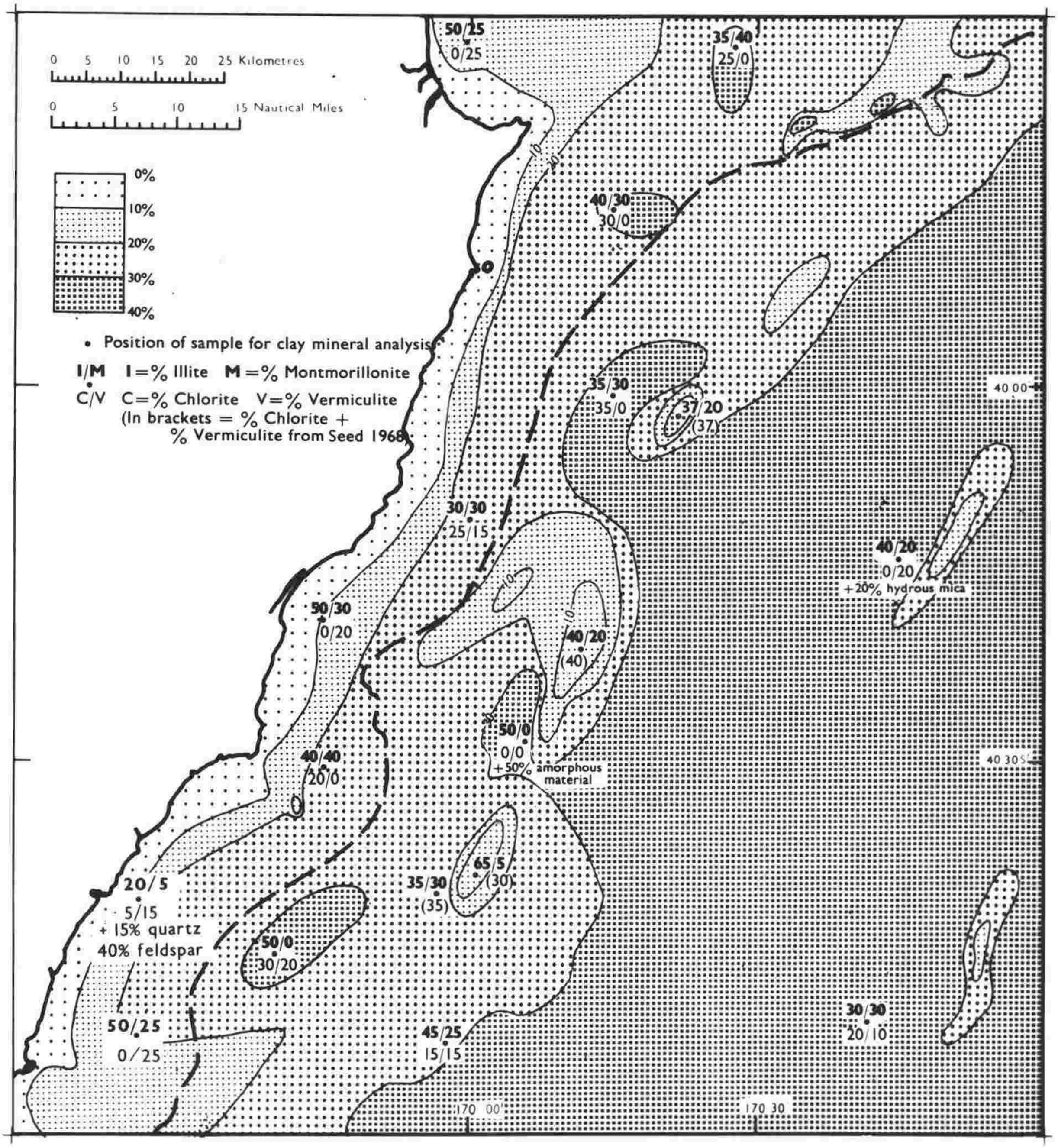

0 5 10 15 20 25 Kilometres
0 5 10 15 Nautical Miles
0%
10%
20%
30%
40%
• Position of sample for clay mineral analysis
I/M I=% Illite M=% Montmorillonite
C/V C=% Chlorite V=% Vermiculite
(In brackets = % Chlorite + % Vermiculite from Seed 1968)
50/25
0/25
35/40
25/0
40/30
30/0
35/30
35/0
37/20
(37)
30/30
25/15
40/20
0/20
+20% hydrous mica
50/30
0/20
40/20
(40)
50/0
0/0
+50% amorphous material
40/40
20/0
65/5
(30)
35/30
(35)
20/5
5/15
+ 15% quartz
40% feldspar
50/0
30/20
50/25
0/25
45/25
15/15
30/30
20/10
10
20
30
40 00
40 30 S
170 00
170 30

Fig. 28

N.Z. Soil Bureau, D.S.I.R. Lower Hutt, using standard X-ray diffraction techniques (Fieldes 1968). Illite, the most abundant clay mineral, constitutes 30-50% of the clay fraction, the montmorillonite content ranges from 0-40% and chlorite and vermiculite are present in most samples. Clay sized quartz and feldspar are present in a single sample from off the mouth of the Owahanga River and amorphous material forms 50% of the clay fraction of a probably pre-Upper Quaternary sample from the Madden Depression.

Frequency curves (Fig. 29), which describe the grain size distribution of the whole sediment, were derived from cumulative curves by the method described by Krumbein (1934). They show that the modal grain size and the mean grain size decrease gradually offshore, that the dispersion increases offshore and that sediments on the outer shelf and upper slope have a conspicuous tail of finer material. Most samples are bimodal with a secondary mode of fine silt or clay size. Each frequency curve can be defined by four statistical parameters, graphic mean, inclusive graphic

FIGURE CAPTION

FIGURE 29

Frequency curves of nine samples. Fine broken line shows position of assumed portion of the curve. Thick broken line joins the main modes.

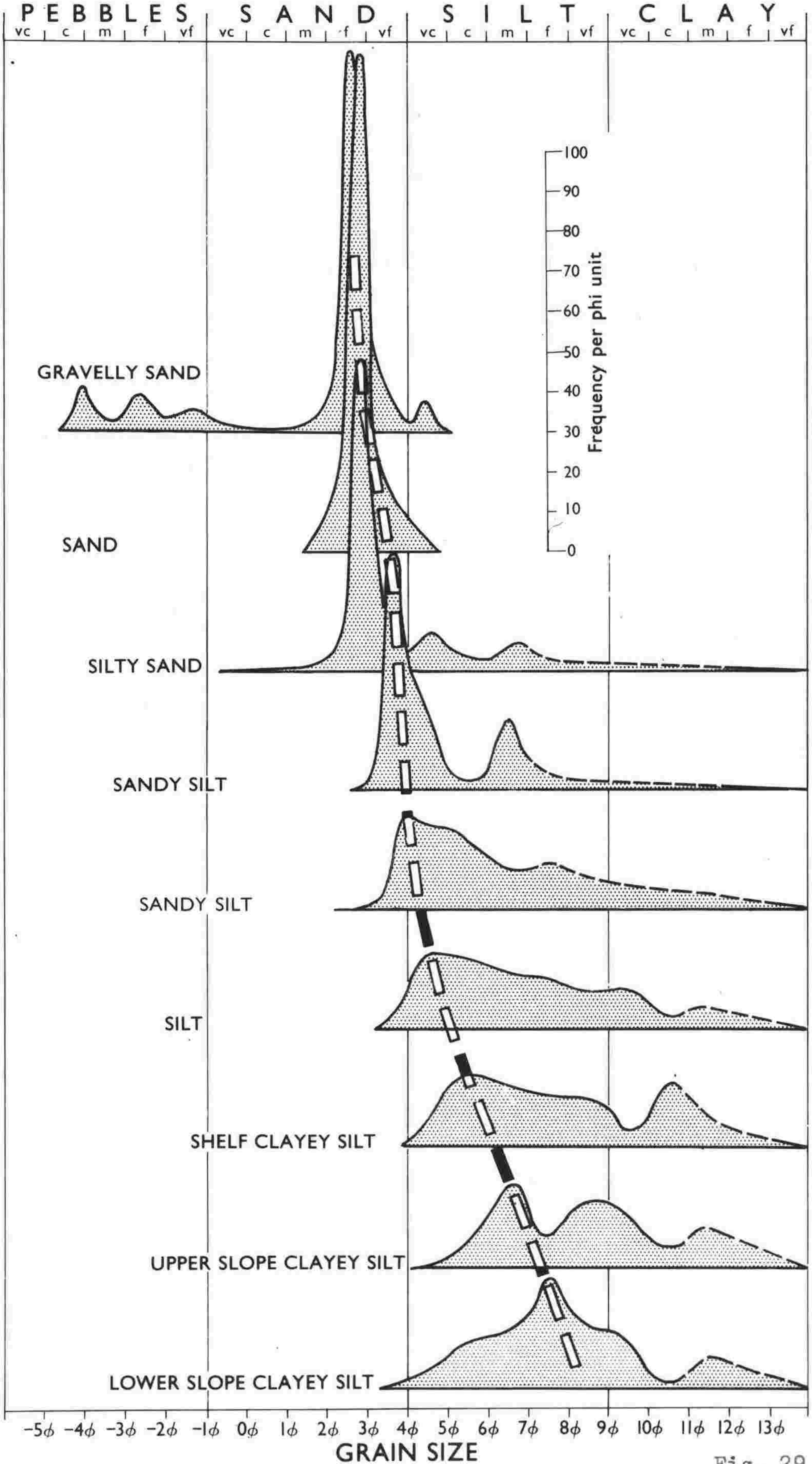

PEBBLES
SAND
SILT
CLAY
vc
c
m
f
vf
Frequency per phi unit
0
10
20
30
40
50
60
70
80
90
100
GRAVELLY SAND
SAND
SILTY SAND
SANDY SILT
SANDY SILT
SILT
SHELF CLAYEY SILT
UPPER SLOPE CLAYEY SILT
LOWER SLOPE CLAYEY SILT
-5ϕ
-4ϕ
-3ϕ
-2ϕ
-1ϕ
0ϕ
1ϕ
2ϕ
3ϕ
4ϕ
5ϕ
6ϕ
7ϕ
8ϕ
9ϕ
10ϕ
11ϕ
12ϕ
13ϕ
GRAIN SIZE

Fig. 29

standard deviation, inclusive skewness and graphic kurtosis (Folk and Ward 1957). The parameters are also derived from cumulative curves. Mean and standard deviation are measures of the central size and spread of the distribution, skewness and kurtosis are measures of the departure from a Gaussian normal distribution. The parameters were computed using a linear interpolation of points on a plot of cumulative frequency against grain size in phi units. Each parameter show marked changes with distance from shore (Figs 30, 31, 32, 33) and depth (Fig. 34).

Mean grain size decreases rapidly seawards on the continental shelf and slowly seawards on the continental slope (Fig. 30, 34). Sediments with the same mean grain size as sediments on the inner continental shelf occur on the continental slope ridges.

Standard deviation is a measure of dispersion. It does not necessarily measure the degree to which the sediment has been sorted and, because values generally decrease with increase of sorting, it may more accurately be said to measure

FIGURE CAPTION

FIGURE 30

Chart showing contours of mean grain size. Broken line is at edge of continental shelf.

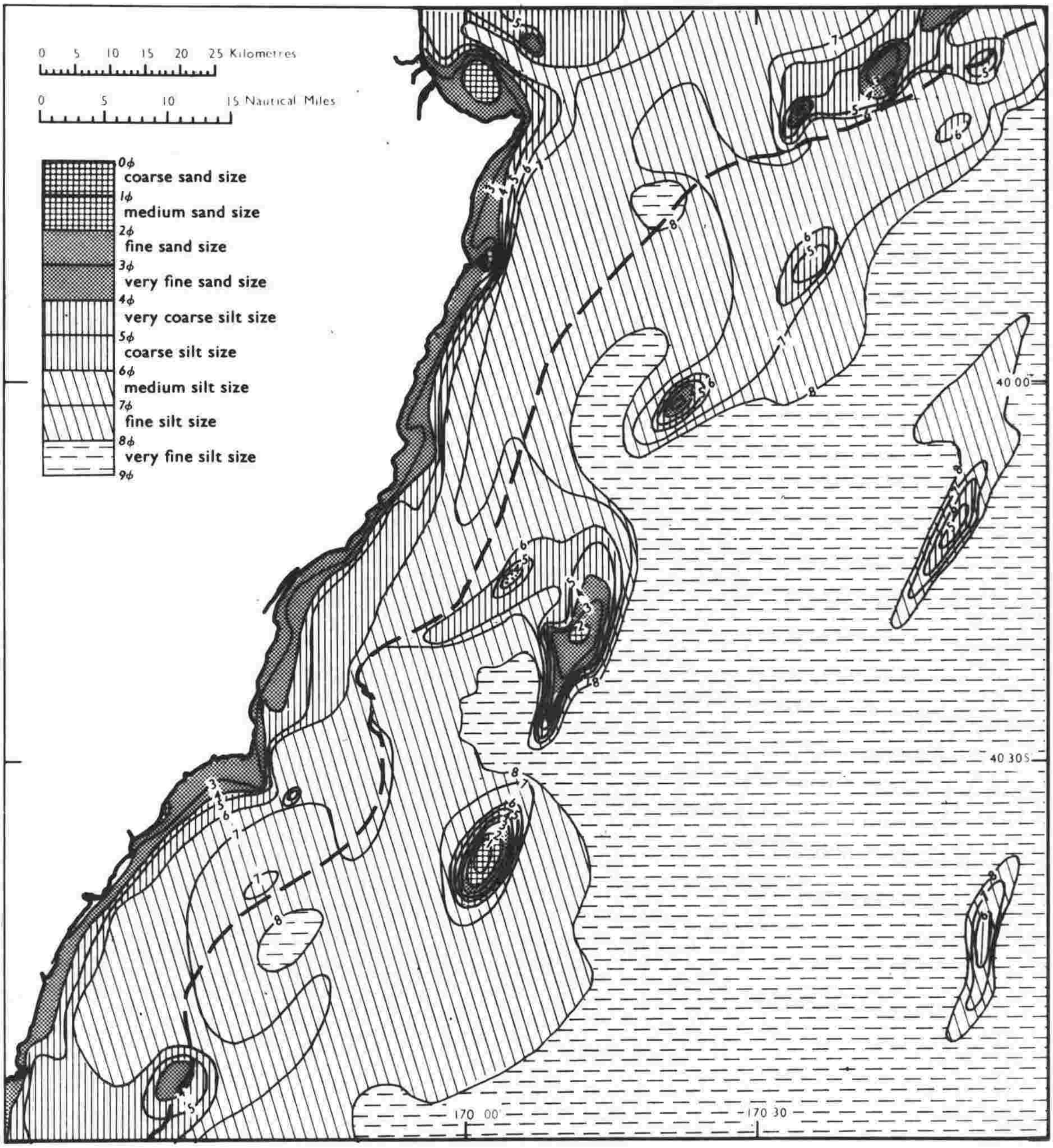

0 5 10 15 20 25 Kilometres
0 5 10 15 Nautical Miles
0φ
coarse sand size
1φ
medium sand size
2φ
fine sand size
3φ
very fine sand size
4φ
very coarse silt size
5φ
coarse silt size
6φ
medium silt size
7φ
fine silt size
8φ
very fine silt size
9φ
40 00
40 30 S
170 00
170 30

Fig. 30

FIGURE CAPTION

FIGURE 31

Chart showing contours of standard deviation. Broken line is at edge of continental shelf.

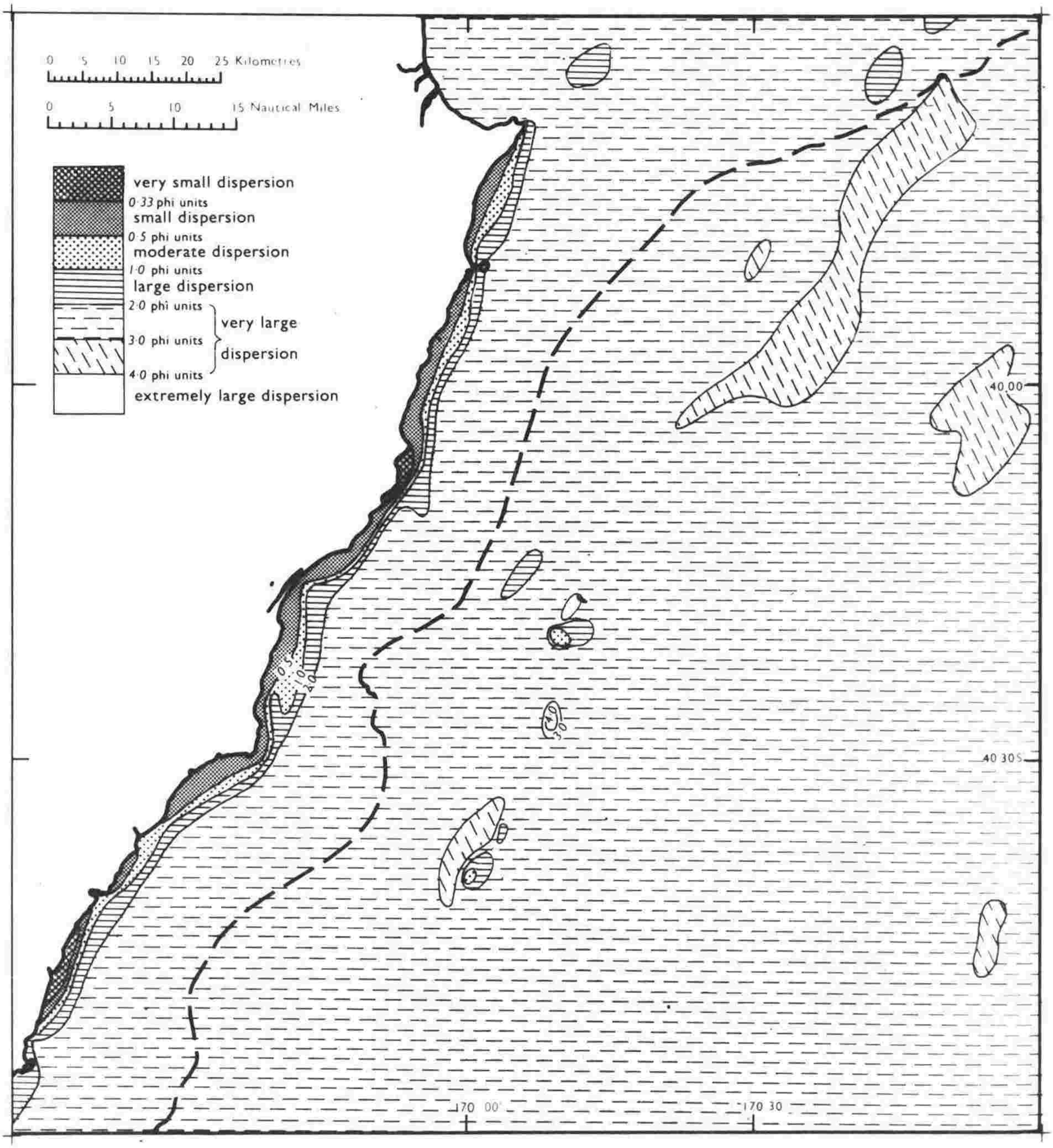

0 5 10 15 20 25 Kilometres
0 5 10 15 Nautical Miles
very small dispersion
0·33 phi units
small dispersion
0·5 phi units
moderate dispersion
1·0 phi units
large dispersion
2·0 phi units
very large dispersion
3·0 phi units
4·0 phi units
extremely large dispersion
0·5
1·0
2·0
4·0
3·0
40 00
40 30 S
170 00
170 30

Fig. 31

FIGURE CAPTION

FIGURE 32

Chart showing contours of skewness. Broken line is at edge of continental shelf.

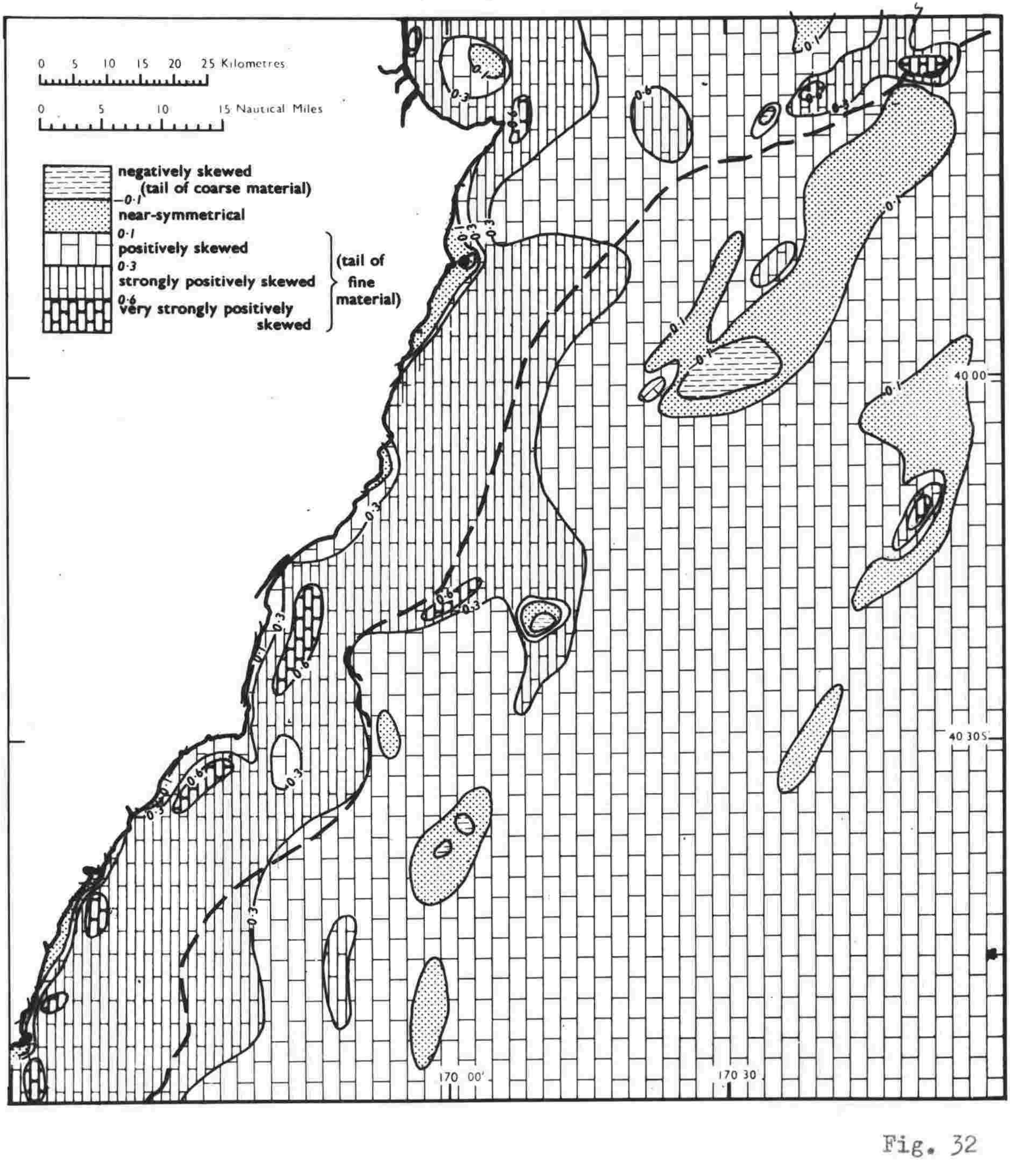

0 5 10 15 20 25 Kilometres
0 5 10 15 Nautical Miles
negatively skewed (tail of coarse material)
-0·1
near-symmetrical
0·1
positively skewed
0·3
strongly positively skewed
0·6
very strongly positively skewed
(tail of fine material)
0·1
0·3
0·6
40 00'
40 30'S
170 00'
170 30'

Fig. 32

FIGURE CAPTION

FIGURE 33

Chart showing contours of kurtosis. Broken line is at edge of continental shelf.

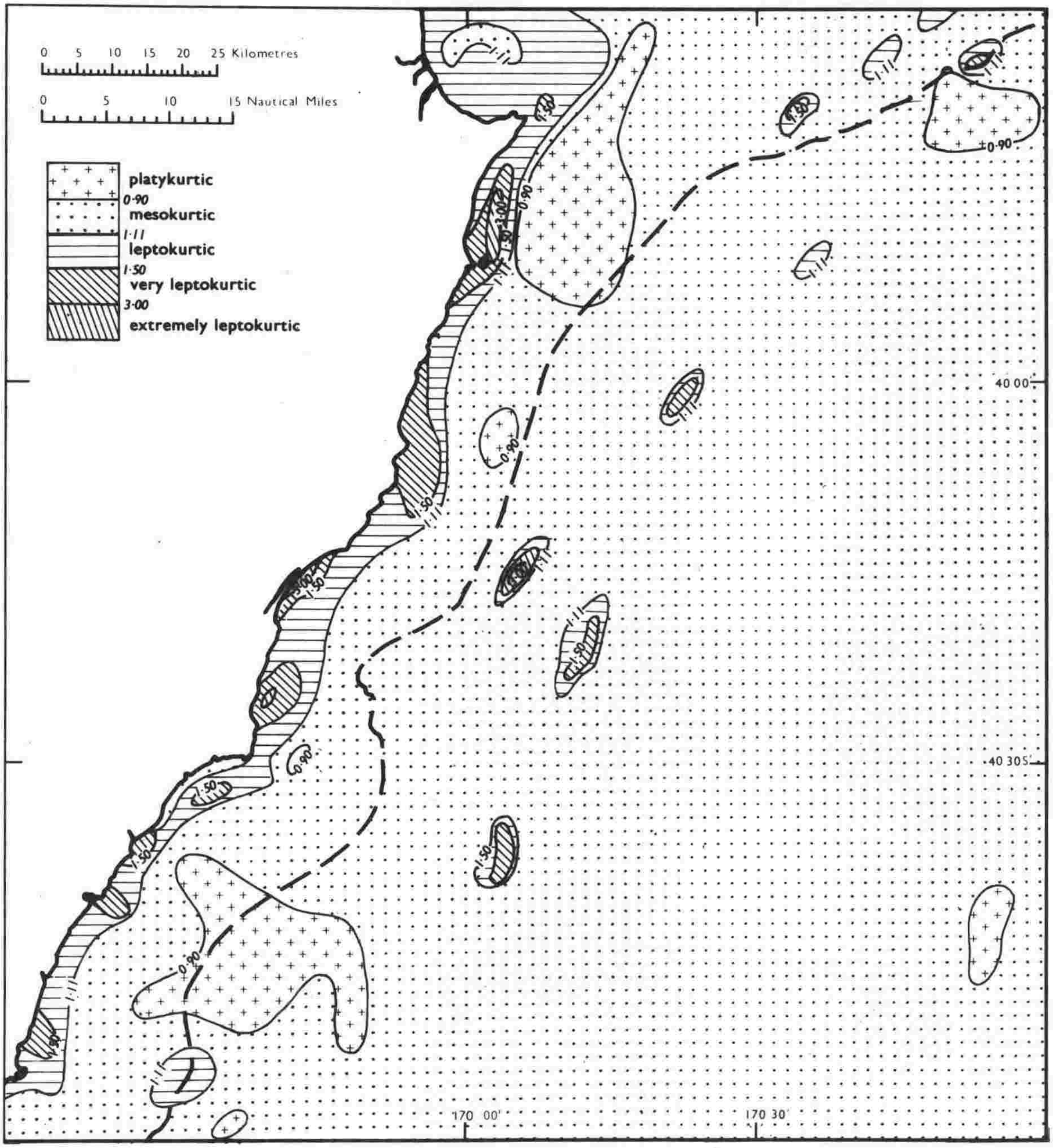

0 5 10 15 20 25 Kilometres
0 5 10 15 Nautical Miles
platykurtic
0·90
mesokurtic
1·11
leptokurtic
1·50
very leptokurtic
3·00
extremely leptokurtic
40 00'
40 30S'
170 00'
170 30'
0·90
1·11
1·50
3·00

Fig. 33

FIGURE CAPTION

FIGURE 34

Plots of depth, from which samples were collected, against grain size mean, standard deviation, skewness and kurtosis. 2 = sand facies, 3 = silty sand facies, 4 = sandy silt facies, 5 = shelf clayey silt facies, 6 = upper slope clayey silt facies, 7 = lower slope clayey silt facies, dots = relict and bank sediments. Lines through numbers drawn by eye. Broken lines group most of samples from each facies. Vertical broken line is at 200m - about the depth of the shelf edge.

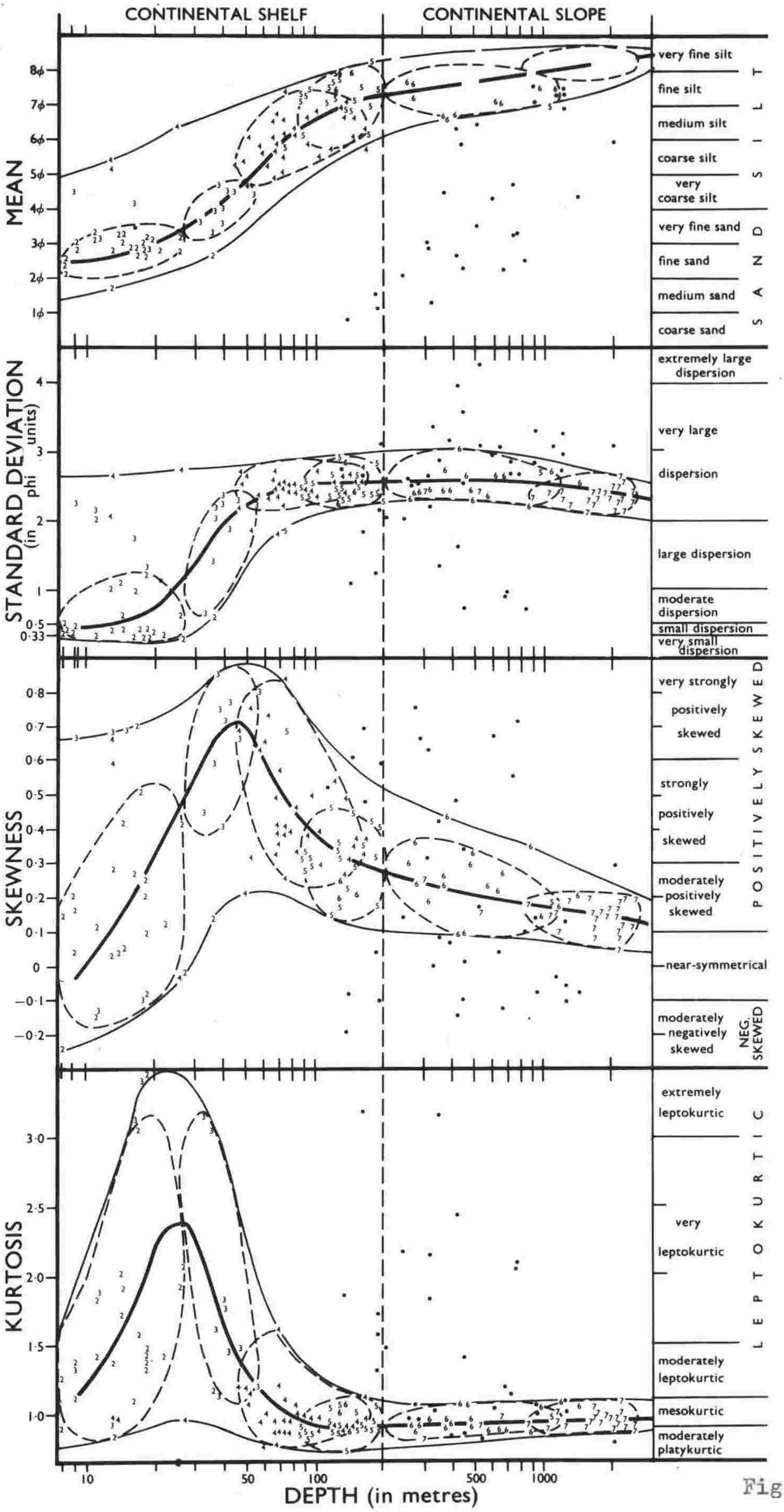

CONTINENTAL SHELF
CONTINENTAL SLOPE
MEAN
8φ
7φ
6φ
5φ
4φ
3φ
2φ
1φ
very fine silt
fine silt
medium silt
coarse silt
very coarse silt
very fine sand
fine sand
medium sand
coarse sand
SILT
SAND
STANDARD DEVIATION (in phi units)
4
3
2
1
0.5
0.33
extremely large dispersion
very large dispersion
large dispersion
moderate dispersion
small dispersion
very small dispersion
SKEWNESS
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
very strongly positively skewed
strongly positively skewed
moderately positively skewed
near-symmetrical
moderately negatively skewed
POSITIVELY SKEWED
NEG. SKEWED
KURTOSIS
3.0
2.5
2.0
1.5
1.0
extremely leptokurtic
very leptokurtic
moderately leptokurtic
mesokurtic
moderately platykurtic
LEPTOKURTIC
10
50
100
500
1000
DEPTH (in metres)

Fig. 34

the amount that the sediment has been mixed (Spencer 1963). It is debatable whether a very skewed sand with a moderate dispersion is better sorted than a near symmetrical clay with a large dispersion. Dispersion increases rapidly seawards on the inner continental shelf and has about the same value at most places to seaward of the inner continental shelf.

Skewness values are positive, indicating a tail of fine grains, at most places in the study area (Figs 32, 34). Sediments are most strongly positively skewed on the middle continental shelf off some rivers. Near-symmetrical and negatively skewed sediments are recorded only from close to the shore and from some continental slope banks.

Mesokurtic sediments cover most of the study area (Figs 33, 34). Leptokurtic sediments, which usually have small amounts of a grain type that is either much smaller or much larger than most of the grains, occur near the coast and on the offshore ridges. Platykurtic sediments, which are usually bimodal with nearly equal proportions of two grain types, occur at some places on the middle and outer continental shelf and on some continental slope ridges.

The changes in the parameters from shore to upper continental slope (Fig. 35) are similar in many ways to the changes produced by increasing the proportion of a fine fraction in a theoretical mixture of fine and coarse fractions (Folk and Ward 1957). Near the shore, fine sand represents a coarse fraction with an almost Gaussian normal grain size distribution. Small amounts of a fine (silt) fraction increase the dispersion of the fine sand and make it positively skewed and leptokurtic. The most leptokurtic sediments are fine sands with about 10% of the fine population : the most positively skewed sediments contain about 20% of the fine population. The sediments with the largest dispersion are conspicuously bimodal and contain about equal proportions of coarse and fine populations. Plots of standard deviation and kurtosis against skewness are circular (Fig. 36) so that a three-dimensional plot of mean, standard deviation and skewness is helical. The sediments in the study area differ from the theoretical example in that the two populations

FIGURE CAPTION

FIGURE 35

Plots of mean grain size against standard deviation, skewness and kurtosis. Vertical line at 64 microns. 1 = gravelly sediment, 2-7 as Fig. 34. Plots show same relationships of parameters as theoretical mixtures of two near-normal sediment fractions (Folk and Ward 1957).

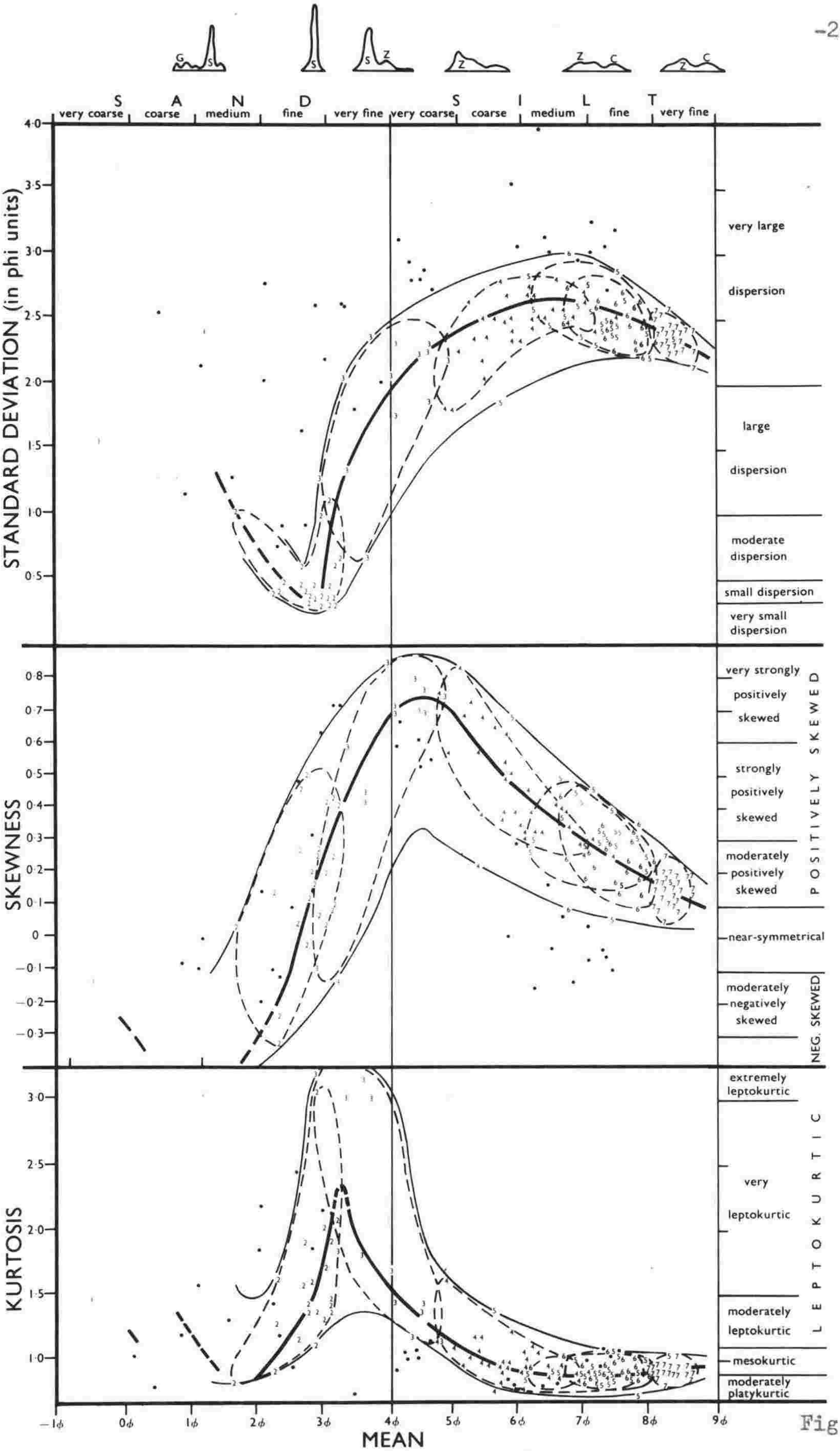

G
S
S
S
Z
Z
Z
C
Z
C
S A N D
S I L T
very coarse
coarse
medium
fine
very fine
very coarse
coarse
medium
fine
very fine
STANDARD DEVIATION (in phi units)
4·0
3·5
3·0
2·5
2·0
1·5
1·0
0·5
very large
dispersion
large
dispersion
moderate
dispersion
small dispersion
very small
dispersion
SKEWNESS
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
−0·1
−0·2
−0·3
very strongly
positively
skewed
strongly
positively
skewed
moderately
positively
skewed
near-symmetrical
moderately
negatively
skewed
POSITIVELY SKEWED
NEG. SKEWED
KURTOSIS
3·0
2·5
2·0
1·5
1·0
extremely
leptokurtic
very
leptokurtic
moderately
leptokurtic
mesokurtic
moderately
platykurtic
LEPTOKURTIC
−1φ
0φ
1φ
2φ
3φ
4φ
5φ
6φ
7φ
8φ
9φ
MEAN

Fig. 35

FIGURE CAPTION

FIGURE 36

Plots of skewness against standard deviation and kurtosis. Numbers etc. as Fig. 35. Vertical line is at zero skewness. Plots are circular, as are plots for theoretical mixtures of two near-normal fractions (Folk and Ward 1957).

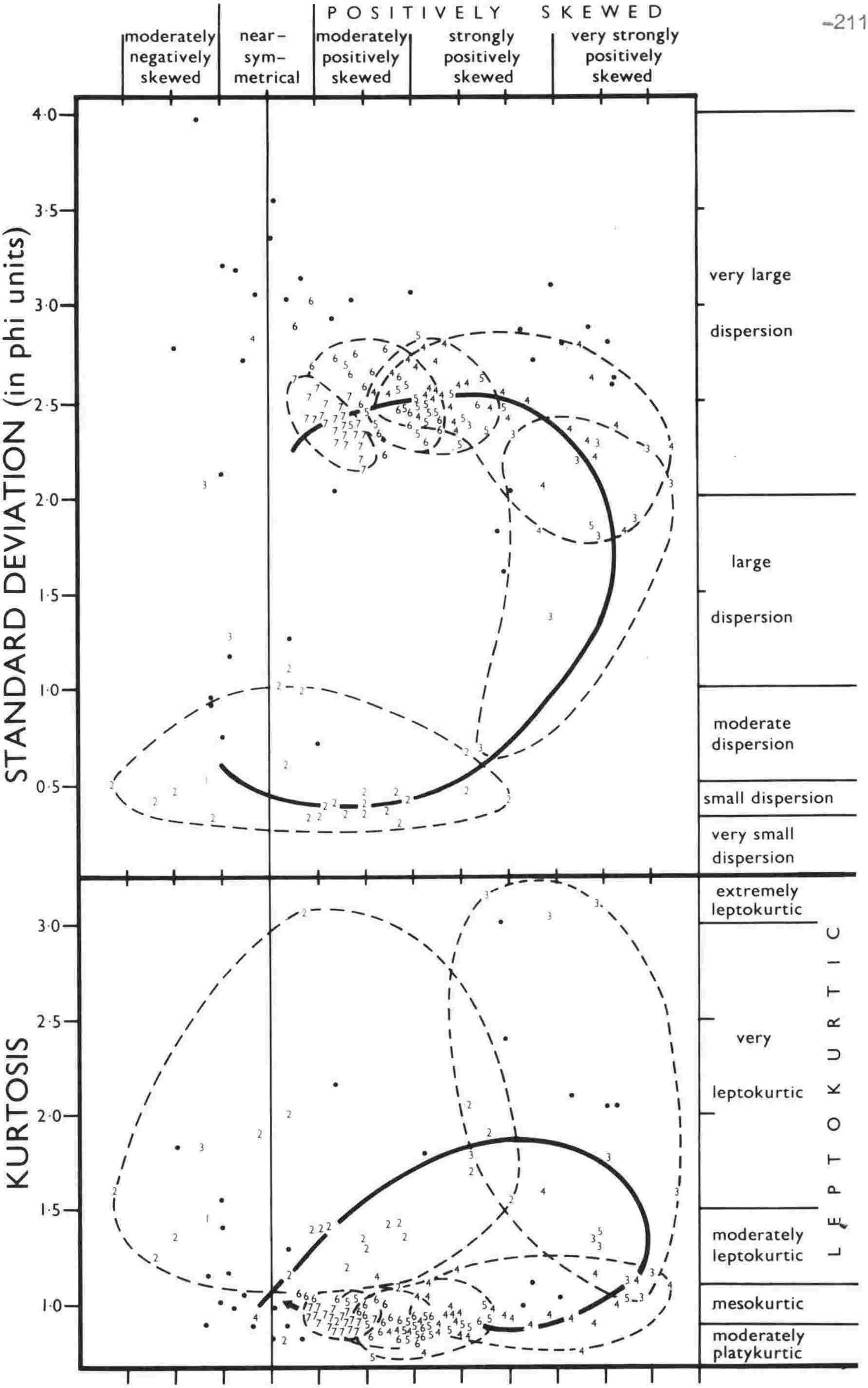

POSITIVELY SKEWED
moderately negatively skewed
near-symmetrical
moderately positively skewed
strongly positively skewed
very strongly positively skewed
STANDARD DEVIATION (in phi units)
4·0
3·5
3·0
2·5
2·0
1·5
1·0
0·5
very large dispersion
large dispersion
moderate dispersion
small dispersion
very small dispersion
KURTOSIS
3·0
2·5
2·0
1·5
1·0
extremely leptokurtic
very leptokurtic
moderately leptokurtic
mesokurtic
moderately platykurtic
LEPTOKURTIC

Fig. 36

have different dispersions and the mode of each population is different in different places. The mode of the coarse population becomes finer seawards more rapidly than the mode of the fine population so that on the continental slope the modes of the coarse and the fine population tend to the same value and the frequency curve becomes almost normal.

Thus, in general detrital sediments decrease in grain size seawards - as would be expected. However, there are patches of coarse sediment that are surrounded by fine sediment. Because coarse detrital grains are not normally transported to seaward of an area where fine detrital grains are settling, the coarse sediments may be either relict and lag deposits or non-detrital deposits. The coarse sediments on the continental shelf and on the uppermost continental slope are considered to be relict sediments because they contain a sand and gravel fraction that is mainly of detrital origin. The coarse sediments on the continental slope banks are considered to be non-detrital because they contain a sand and gravel fraction that is predominantly of non-detrital grains such as volcanic ash, foraminiferal tests, glauconite, brachiopods, molluscs, bryozoa and corals.

SEDIMENTARY FACIES *

Modern Detrital Sediments

Sand Facies:

Classification : Sand (fine sand)
Size grades : gravel <5%, sand >90% of sand + mud, silt 77-89% of mud.
Sand minerals : detrital >95%.
Mode : 2.5 - 3.0 Ø
Parameters : M_z 2.0-3.2 Ø, σ_I 0.3-1.1 phi units, Sk_I -0.2-+0.5, K_G 0.9-3.0
To shore : inner 0km, outer <4km
Depth : top 0m, bottom <30m.

At most places sand facies sediments consist of an almost normal population of fine sand size with a small dispersion. Off most river mouths the sand

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* Data given at beginning of each facies description applies to at least 90% of samples. Underlined data define each facies.

contains sufficient fine silt and clay to make it very leptokurtic. Off some river mouths a larger proportion of fine grains also makes the sand strongly positively skewed. Off the Porangahau River, sand with almost 10% mud has a large dispersion, is very strongly positively skewed and extremely leptokurtic.

Silty Sand Facies:

Classification : silty sand (very coarse silty, fine or very fine sand).
Size grades : gravel<1%, sand 50-90% of sand + mud, silt 76-89% of mud.
Sand minerals : detrital>90%.
Mode : 2.8 - 3.5 ϕ
Parameters : M_z3.0-4.8 ϕ, σ_I0.7-2.4 phi units, Sk_I0.4-0.9, K_G1.2-3.1.
To shore : inner 0-4km, outer 1-14km.
Depth : top 0-40m, bottom 10-60m.

Silty sands are most strongly skewed and most leptokurtic near the rivers south of Cape Turnagain, 15-20km south of the Porangahau River and off Cape Kidnappers, which is 20km east of southern Hawke Bay river mouths. Silty sands occur at shallow depths in southern Hawke Bay which is sheltered from southerly swells (Gibb 1962).

Sandy Silt Facies:

Classification : sandy silt and sandy clayey silt, (very fine sandy, very coarse silt).

Size grades : gravel $<0.5\%$, sand 10-50% of sand + mud, silt 72-88% of mud.

Sand mineral : detrital $>80\%$, volcanic $<15\%$, carbonate $<15\%$.

Mode : 3.0 - 4.0 Ø

Parameters : M_z4.7-7.4 Ø, σ_I1.8-2.7 phi units, Sk_I0.2-0.8, K_G0.8-1.6.

To shore : inner 3-10km, outer 4-30km.

Depth : top 13-60m, bottom 80-200m.

Sediments of sandy silt facies are conspicuously bimodal with a primary mode of very fine sand size and a secondary mode of medium or fine sand size. They have higher values for dispersion and lower values for kurtosis than most sediments to landward. Samples off the Porangahau River and off some rivers to the south of Cape Kidnappers are extremely strongly positively skewed.

Shelf Clayey-silt Facies:

Classification : silt and clayey-silt (mainly clayey, coarse or very coarse silt)

Size grades : sand 0.3-10%, silt 63-77% of mud.

Sand minerals : detrital 50-85%, volcanic 10-45%, carbonate 5-30%, glauconite < 5%.

Mode : 4 - 6 Ø.

Parameters : M_z6.1-8.0 Ø, σ_I1.9-2.9 phi units, Sk_I0.1-0.5, K_G0.8-1.1.

To shore : inner 4-30km, outer 18-50km.

Depth : top 80-160m, bottom 150-1100m.

Shelf clayey-silts differ from other clayey-silts in having a predominance of detrital grains in the sand fraction. At some places they are bimodal with a secondary mode of fine or very fine silt size. It is generally less strongly skewed than sediments to landward.

Upper Slope Clayey-silt Facies:

Classification : clayey-silt, (clayey, coarse or medium silt).
Size grades : sand 0.4-10%, silt 63-73% of mud.
Sand minerals : detrital 5-50%, volcanic 25-85%, carbonate 20-70%, glauconite <10%.
Mode : 5 - 7 φ
Parameters : M_z6.7-8.0 φ, σ_I2.3-3.1 phi units, Sk_I0.1-0.4, K_G0.9-1.1.
To shore : inner 16-35km, outer 22-80km.
Depth : top 100-300m, bottom 700-2000m.

Upper slope clayey-silts differ from shelf clayey-silts in having a predominantly non-detrital sand fraction and from lower slope clayey-silts in having a mean diameter coarser than 8φ. Most of the carbonate grains in the sand fraction are planktonic foraminifera.

Lower Slope Clayey-silt Facies:

Classification : clayey-silt (clayey medium or fine silt).

Size grades : sand 0.5-5%, silt 59-65% of mud

Sand minerals : detrital < 10%, volcanic 25-90%, carbonate 20-75%.

Mode : 6 - 8 Ø.

Parameters : M_z 8.0-8.7 Ø, σ_I 2.1-2.7 phi units, Sk_I 0-0.2, K_G 0.9-1.1.

To shore : inner 22-80km, outer > 120km.

Depth : top 300-2000m, bottom > 2500m.

Lower slope clayey-silts differ from other clayey-silts in having a mean diameter of very fine sand size and lower values of dispersion and skewness than most clayey-silts to landward. In the northern part of the area the sand fraction is predominantly volcanic ash, whereas in the southern part of the area it is predominantly calcareous foraminifera.

Relict Detrital Sediments

Gravelly Facies:

Classification : gravelly muddy sand (pebble gravelly silty fine sand).

Size grades : gravel 5-25%, sand 60-90% of sand + mud, silt 75-93% of mud.

Sand mineral : detrital 95%.
Mode : 2.5 - 3.5 Ø, other modes in pebble size grade.
Parameters : M_z0-2 Ø, σ_I2.3-2.9 phi units, Sk_I-0.7-+0.1, K_G1.5-3.0.
To shore : inner 1-2km, outer 4-9km.
Depth : top 10-20m, bottom 15-60m.

Sediments of gravelly facies contain pebbles of hard rock and occur on the inner continental shelf. Some pebbles are partly encrusted with worm tubes and bryozoans.

Lachlan Ridge Facies:

Classification : clayey-silty sand, pebble gravelly muddy sand, calciruditic muddy sand.
Size grades : gravel 2-15%, sand 50-85% of sand + mud, silt 66-73% of mud.
Sand minerals : detrital 40-75%, volcanic 12-50%, carbonate <20%.
Mode : 1 - 3 Ø.
Parameters : M_z1-5 Ø, σ_I2.3-2.9 phi units, Sk_I-0.2-+0.7, K_G1.0-1.9.

To shore : -50km.
Depth : 80-180m.

Sediments of the Lachlan Ridge facies, which are described originally by Pantin (1966) are very variable, probably occurring in isolated patches between rocky outcrops. They have a gravel fraction of subangular pebbles and mollusc shells and a sand fraction of sand-sized mudstone fragments, terrigenous detrital grains and volcanic ash. They occur at the Lachlan Ridge and at the Turnagain Banks on the middle continental shelf off Cape Turnagain.

The mollusc fauna at the Lachlan Ridge has been identified by Dr A.G. Beu of the N.Z. Geological Survey and includes the -

bivalves: *Angulus edgari* Iredale, *Dosinia (Asa) lambata* (Gould), *Gari lineolata* (Gray), *Maorimactra ordinaria* (Smith), *Neilo australis* (Quoy and Gaimard), *Nucula hartvigiana* Dohrn, *Nucula nitidula* Adams, *Nucula strangei* Adams, *Poroleda lanceolata* (Hutton), *Tellinella huttoni* (Smith), *Scalpomactra scalpellum* (Reeve), *Tellinota edgari* (Iredale).

gastropods: *Acteon craticulatus* Hedley, *Amalda (Brachyspira) depressa* (Sowerby), *Amalda (Brachyspira) mucronata* (Sowerby), *Amalda (Gracilispira) novaezelandiae* (Sowerby), *Antisolarium egenum* (Gould), *Austrofusus glans* (Röding), *Pervicacia tristis* (Deshayes), *Phenatoma zelandica* (Smith).

scaphopods: *Cadulus delicatulus* Suter, *Dentalium nanum* Hutton.

Many of the shells are broken and some are worn. Some are normally shallow-water forms and may have been deposited during low sea level of the Last Glacial Age. Mudstone pebbles at the Turnagain Banks have been bored and contain specimens of the bivalve *Pholadidea tridens* (Grey) *in situ*.

Porangahau Slope Facies:

Classification : silty sand, sandy silt, sandy clayey-silt.

Size grades : *gravel 0.5%*, *sand 10-77%*, silt 67-84% of mud.

Sand minerals : *detrital 40-90%*, *volcanic* 50%, carbonate <20%, glauconite <5%.

Mode : 3 - 6 ϕ.

Parameters : M_z 3.7-7.2 ϕ, σ_I 1.3-2.8 phi units, Sk_I 0.1-0.8, K_G 0.9-3.2

To shore : 18-30km

Depth : 200-1000m.

Sediments of Porangahau slope facies contain no pebbles, no mudstone fragments and few shells. They occur on the upper continental slope to the north and south of the Madden Depression. They are similar to sediments on the inner continental shelf but contain a higher proportion of volcanic ash, foraminifera and glauconite than most shelf sediments. Gravity cores from the area to the north of the Madden Depression (Fig. 37) show that the sediment more than 100-500mm beneath the seabed is more muddy than the sediment at the seabed. The sediment throughout each core is extensively disturbed by boring organisms and the boundary between surface sediment and underlying mud is diffuse. Porangahau slope facies are underlain by mud whereas Lachlan facies are underlain by rock.

FIGURE CAPTION

FIGURE 37

Diagrammatic logs of gravity cores from areas of relict and bank sediments.

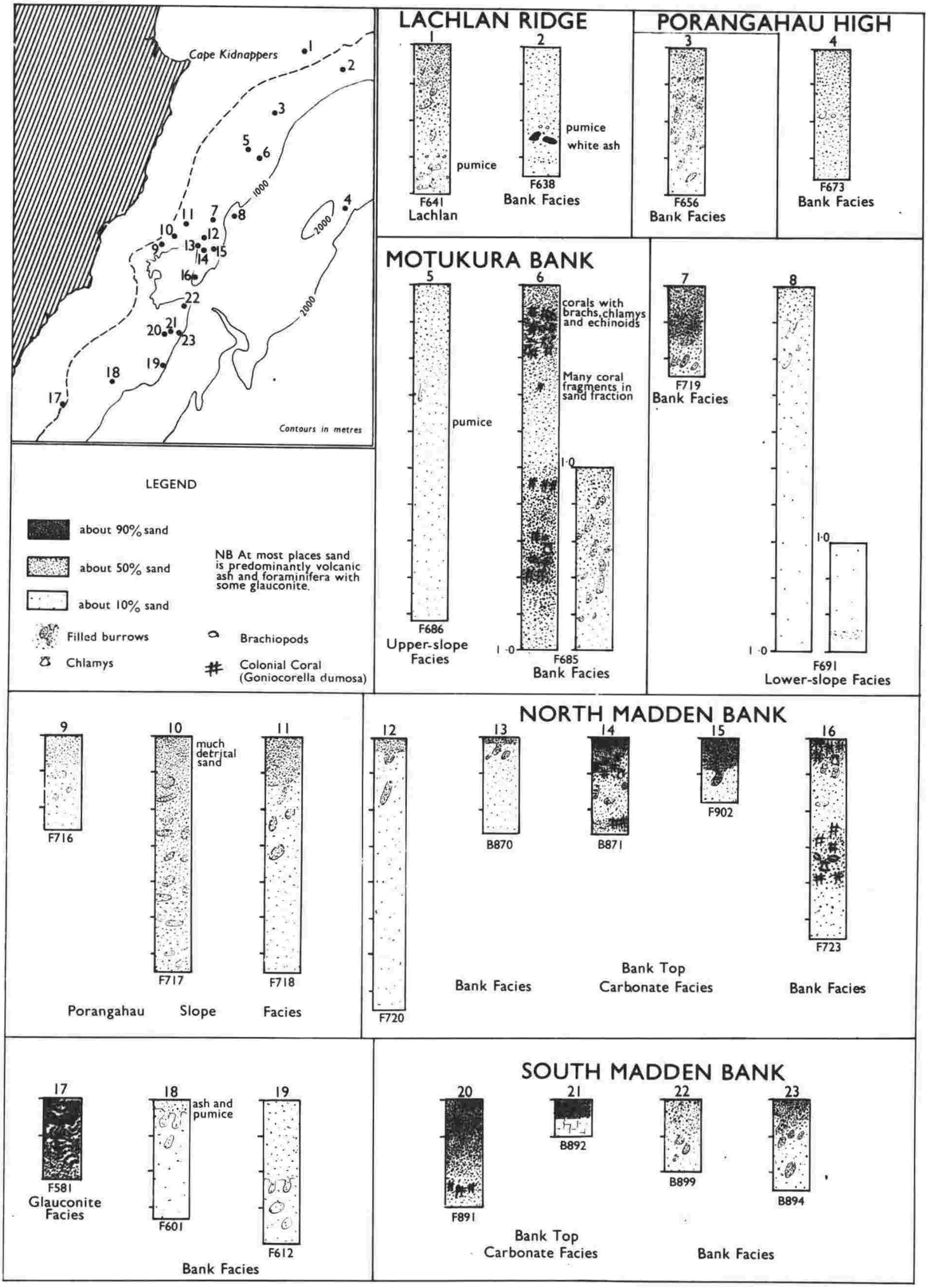
Cape Kidnappers
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
1000
2000
2000
Contours in metres
LEGEND
about 90% sand
about 50% sand
about 10% sand
NB At most places sand is predominantly volcanic ash and foraminifera with some glauconite.
Filled burrows
Chlamys
Brachiopods
Colonial Coral (Goniocorella dumosa)
LACHLAN RIDGE
pumice
pumice
white ash
F641
Lachlan
F638
Bank Facies
PORANGAHAU HIGH
F656
Bank Facies
F673
Bank Facies
MOTUKURA BANK
pumice
corals with brachs, chlamys and echinoids
Many coral fragments in sand fraction
1·0
1·0
F686
Upper-slope Facies
F685
Bank Facies
F719
Bank Facies
1·0
1·0
F691
Lower-slope Facies
much detrital sand
F716
F717
F718
Porangahau Slope Facies
NORTH MADDEN BANK
F720
B870
B871
F902
F723
Bank Facies
Bank Top Carbonate Facies
Bank Facies
ash and pumice
F581
Glauconite Facies
F601
F612
Bank Facies
SOUTH MADDEN BANK
F891
B892
B899
B894
Bank Top Carbonate Facies
Bank Facies

Fig. 37

Glauconite Facies:

Classification : silty sand, sandy silt.

Size grades : sand 30-65%, silt 76-83% of mud,

Sand minerals : detrital 40-75%, volcanic <10%, carbonate <10%, glauconite 20-45%.

Mode : 3.5 - 5 ϕ.

Parameters : M_z3.8-5.8 ϕ, σ_I2.0-2.8 phi units, Sk_I0.4-0.5, K_G1.1-1.5.

To shore : 18 - 30km.

Depth : 160 - 250m.

The glauconite facies occur near the shelf break off Castlepoint. It consists of sediments that are similar to, but contain a higher proportion of glauconite than, sediments on the inner continental shelf.

Non-Detrital Sediments

Bank Facies:

Classification : clayey-silty sand, sandy clayey-silt, calcarenitic clayey-silt, calciruditic muddy sand.

Size grade : gravel < 12% (carbonate), sand 10-80% of sand + mud, silt 62-73% of mud.
Sand minerals : detrital < 10%, volcanic 30-85%, carbonate 10-60%, glauconite < 30%.
Mode : 3 - 6 Ø
Parameters : M_Z2.0-7.4 Ø, σ_I2.0-4.3 phi units, Sk_I-0.2-+0.7, K_G0.8-2.2.
To shore : 30 - 1100km.
Depth : 200 - 2000m.

Bank facies sediments occur on most banks and ridges on the continental slope. They include sediments with more than 10% sand-sized grains but exclude the calcarenites and calcirudites that occur on the tops of some banks. At most places the sand fraction is predominantly volcanic ash with subdominant foraminiferal tests and some glauconite. At some places the sand fraction includes broken molluscs and coral fragments. Bank facies sediments have a much larger dispersion than near shore sediments of similar mean grain size.

Many cores from banks on the upper continental slope are coarse at the top and either become gradually finer downwards (Fig. 37) or show a distinct horizon below which the sediment is less sandy. The underlying less sandy sediment contains burrows filled with sandy surface sediment and colonial corals identified as Goniocorella dumosa (Alcock). Amongst the corals were fragments of echinoids identified by D.G. McKnight (N.Z. Oceanographic Institute) as belong to the genera Pseudechinus and Goniocidaris (?Petalocidaris). Less sandy sediment with Goniocorella crops out on the west side of the Motukura Bank and at the southern end of the North Madden Bank. Some cores from banks on the lower continental slope become finer downwards (Fig. 37, Core 4).

Bank Top Carbonate Facies:

Classification : Calcarenite, calciruditic calcarenite, muddy calcarenite, muddy calcarenitic calcirudite.

Size grades : gravel 1-34% (carbonate), sand 55-98% of sand + mud, silt 66-78% of mud.

Sand minerals : volcanic 5-50%, carbonate 50-85%, glauconite 1-20%.

Mode : 1 - 4 ϕ.

Parameters : M_Z0.1-4.1 ϕ, σ_I0.9-3.1 phi units, Sk_I-0.5-+0.7, K_G0.8-2.2.

To shore : 34 - 40km.

Depth : 160 - 500m.

The Bank Top Carbonate Facies occurs on the tops of the Madden Banks. The sand fraction consists of foraminiferal tests, shell fragments, volcanic ash, glauconite and rare fragments of mudstone. The gravel fraction consists of brachiopods, corals, scallop shells, pteropods and rare fragments of mudstone. Cores pass through the surface calcarenite into either calcarenitic mud or consolidated mudstone of Upper Miocene or Pliocene Age (Fig. 37). Dredge samples of the mudstone are riddled with burrows similar to those formed by the bivalve *Pholadidea tridens* (Gray).

The mollusc fauna from the tops of the Madden Banks has been identified by Dr A.G. Beu and includes the

bivalves: *Bathyarea cybaca* (Hedley), *Chlamys (Mimachlamys) gemmulata* (Reeve), *Chlamys (Mimachlamys) taiaroa* Powell, *Cosa costata* (Bernard), *Cuspidaria morelandi* Dell, *Cyclopecten aupouria* Powell, *Halirus setosa* (Hedley), *Hiatella arctica* (Linnaeus), *Limatula suteri* (Dall), *Limatula maoria* Finlay, *Monia zelandica* (Gray), *Nemocardium pulchellum* (Gray), *Pleuromeris marshalli* Marwick, *Pleuromeris zelandica* (Deshayes), *Venericardia (Purpurocardia) purpurata* (Deshayes).

gastropods: *Anotoma regia* (Mestayer), ?*Antiguraleus* sp., *Asperdaphne expeditionis* Dell, *Austromitra lawsi* Finlay, *Cavolina telemus* (Linnaeus), *Clio pyramidata* (Linnaeus), *Cirsotrema zelebori* (Dunker), *Cominella (Eucominia) alertae* (Dell), *Cominella (Eucominia)* cf. *marlboroughensis* Powell, *Cymatona kampyla delli* Beu, M.S., *Diacria trispinosa* (Lesueur), *Emarginula striatula* (Quoy and Gaimard), *Malluvium calcareum* (Suter), *Marginella* (*Volvarinella*) *subfusula* Powell, *Microvoluta biconica* (Murdoch and Suter), *Mitrithara* sp., *Proxiuber australis* (Hutton), *Splendrillia roseacincta* Dell, *Tanea zelandica* (Quoy and Gaimard), *Terefundus axirugosa* Dell, *Trichosirius inornatus* (Hutton). (The genera *Cavolina*, *Clio* and *Diacria* are pteropods).

scaphopods: *Dentalium* (*Fissidentalium*) *zelandicum* (Sowerby), *Dentalium* (*Laevidentalium*) *ecostatum* Kuln.

Corals from the South Madden Bank are recorded by Squires and Keyes 1967.

Brachiopods were identified by Mr E.W. Dawson (N.Z. Oceanographic Institute) as *Liothyrella neozelandica* Thomson, and *Neothyris lenticularis* (Deshayes).

SEDIMENTATION: ORIGIN AND DEPOSITION

Grains of detrital origin constitute more than 90% of the sediment at most places in the study area. Most of the detrital grains are of terrigenous origin; only a few mudstone pebbles are considered to be of submarine origin. From a comparison of rates of coastal erosion and rates of offshore deposition it has been shown (Lewis, in press b) that only a few percent of the terrigenous detrital grains originate from coastal erosion, the remainder being formed by subaerial erosion are carried to the sea by rivers and wind.

When they reach the sea many of the terrigenous detrital grains pass through the breaker zone where they are sorted into three groups; 1. gravel and coarse sand; 2. fine sand; 3. mud. Much of the gravel is transported to beaches and marooned there because receding waves partly percolate into the beach material. In many cases the gravels migrate landward as a shore line transgresses. It may be therefore, that gravelly sediment on the inner continental shelf represents beach deposits of drowned islands or drowned sand spits. Some angular mudstone fragments may have formed by wave destruction of <u>Pholadidea</u>-bored rocky reefs. Fine sand grains, which are easily moved and held in suspension by turbulent water, are returned by receding waves to the lower part of the beach. The interrelationship of their bed roughness velocity, threshold velocity, settling velocity ensures that most of them remain in near-shore, high energy environments (Inman 1949; Griffiths 1951). Mud grains are held in suspension in the breaker zone and are carried by tidal and coastal currents until they reach the offshore, low energy environment.

Most mud is carried almost parallel to the shore by a southward flowing coastal current whilst sand is moved northwards along the beaches by southerly swells (Lewis, in press b). A current flows into the centre of Hawke Bay and flows out around the northern and southern sides of the bay (Ridgway 1960). The southern branch of the current picks up mud and very fine sand at the mouth of of the three major rivers in southern Hawke Bay, carries it around Cape Kidnappers and deposits it on the middle continental shelf to the south. The movement of muddy water southward from Cape Kidnappers was noted as long ago as 1827 by the explorer D'Urville (Wright 1950).

It is assumed that, during constant flow conditions, a sediment laden current deposits a Gaussian normal population of grain sizes (Wentworth 1929; Krumbein 1938). A non-normal distribution is often attributed to either a deficiency of some grain size in the sediment supplied to the current or deposition of different fractions of the sediment during different flow regimes or winnowing of the fines. A fourth cause, related to the difference in technique whereby current and analyst measure grain size, probably accounts for most of the non-normal grain size distributions described above. In nature grains are sorted according to their settling velocities; in the laboratory they are sorted by sieving of the coarse fraction and settling of the fine fraction after destruction of the flocs. For example, in a

A.F ?
Not clear

sediment composed of volcanic ash, detrital silt and flocs, the analyst sieves off the sand-sized volcanic ash, which forms a coarse mode or tail, and disaggregates the flocs into fine silt and clay grains, which form a fine mode or tail.

Most fine silt and clay grains aggregate to form flocs when they enter the sea. Coarse detrital grains and large flocs (composed of many grains) settle rapidly and are deposited near the shore whereas fine detrital grains and small flocs (composed of few grains) settle slowly and are carried far from the shore. The size of the grains that are deposited singly decreases rapidly with distance from shore whereas the size of the grains that are deposited in flocs remains almost the same. The bimodal sediments on the continental shelf are composed of a coarse (fine sand and coarse silt) mode representing grains deposited singly and a fine (fine silt and clay) mode representing grains that were deposited as flocs. The sediments on the lower continental slope are almost normal because the grains deposited singly are only slightly larger than the grains deposited as flocs.

Relict detrital grains occur in areas where Holocene deposits are thin or absent (i.e. on the innermost continental shelf and near the shelf break (Lewis, in press b) and are considered to have been deposited near the end of the Last Glacial Age. At some places the coarse relict detrital grains have been concentrated by winnowing of the fines and at all places they have been diluted by younger sand grains. The gravelly facies on the innermost shelf consists of beach pebbles mixed with younger detrital sand. The Lachlan facies, the Porangahau slope facies and the Glauconite facies, which all occur near the shelf break, consist of detrital sand and mud and younger non-detrital sand grains. The non-detrital grains are predominantly volcanic ash in the northern part of the study area and predominantly glauconite in the south. The subangular fragments of mudstone that occur in the Lachlan Ridge facies and on the South Madden Bank are probably derived from Pholadidea-bored Tertiary mudstone during a period of low sea level. The Porangahau Slope facies and the

Glauconite facies which both overlie extensively burrowed muddy sediment, were probably winnowed by burrowing organisms stirring fine silt and clay into suspension and leaving coarser grains as a lag deposit.

Non-detrital grains include volcanic ash, authigenic glauconite and organic carbonate. At most places on the continental slope the main constituents of the sand fraction are volcanic ash and tests of planktonic foraminifera. The latter are most important in the southern part of the area, being swamped by volcanic ash in the north. The ash is derived from the volcanoes of central North Island and is carried to the northern part of the area by the prevailing westerly winds and by rivers that drain ash covered hills. At most places volcanic ash and planktonic foraminifera form an insignificant proportion of the whole sediment but on continental slope banks they are an important or even a dominant constituent of the sediment. Relatively little mud reaches the banks either because it is prevented from settling by currents that increase speed as they cross the banks, or because most mud in suspension is well below the surface of the sea and cannot move upslope on to the banks. The banks are a suitable environment for the growth of other types of non-detrital grains including glauconite and shells of benthonic foraminifera, brachiopods, molluscs, corals and echinoderms. Muddy sediment that underlies non-detrital sediment on the upper continental slope is considered to have been deposited during the Last Glacial Age when mud was carried by rivers to the middle continental shelf and was deposited rapidly on the upper continental slope.

It is concluded that most of the surface sediment is composed dominantly of terrigenous detrital grains. The modal grain size ranges from fine sand near the shore to medium silt on the lower continental slope but the sediment at most places includes fine silt and clay grains from disaggregated flocs. At places where the rate of detrital deposition is low, surface sediments contain a significant proportion of either relict detrital grains or non-detrital grains. On the continental shelf and uppermost slope Last Glacial

Age sediment is coarser than sediment being deposited at present whereas on the upper continental slope banks it is finer than sediment being deposited at present.

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PAPER 5

UPPER MIOCENE AND PLIOCENE ROCKS FROM THE CONTINENTAL SHELF AND SLOPE OFF SOUTHERN HAWKES BAY

To be submitted for publication in N.Z. Jl mar. freshwat. Res.

ABSTRACT

Sixteen rock samples are described from the inner continental shelf and from anticlinal ridges on the outer shelf and upper slope of southern Hawkes Bay. Nine of the samples are mudstone containing fossil foraminifera of Upper Miocene and Pliocene age. At most places depths of deposition inferred from the fossil foraminifera are much greater than the depth from which the samples were dredged indicating nett uplift of the seabed at those places since Miocene times. Grain size and mineralogy suggest that all Upper Miocene and Pliocene samples were deposited before the anticlinal ridges began to rise above the surrounding seabed. Thus, the present pattern of folding is post-Miocene in age.

INTRODUCTION

Pantin (1966) described two Eocene samples and a third sample of undetermined age from the Lachlan Ridge, on the outer part of the continental

N.F.: Fig 38
[illegible] and
[illegible]
[illegible]
specimens

shelf off Napier, Hawkes Bay Land District, New Zealand (Fig. 38). A further 16 samples are described below, four from the inner shelf and the remaining 12 from a line of offshore banks and ridges stretching 150km SSW from the Lachlan Ridge. Nine samples can be dated by their foraminiferal fauna and range from Upper Miocene to Pliocene in age.

A study of continuous seismic profiles (Lewis, in press a) has shown that the line of ridges lies along the actively growing Lachlan Anticline. Between the Lachlan Anticline and the inner shelf is the actively subsiding Mahia Syncline, which contains a thick sequence of Late Quaternary beds. Rocks older than Late Quaternary crop out only on the Lachlan Anticline and on the rising inner shelf.

Most of the rock samples were collected using either a dredge or an orange-peel grab; a few were found wedged in the cutter of a short gravity corer. Foraminifera were extracted by normal techniques (Hornibrook 1968) and their ages were estimated using data given by Hornibrook (1961, 1968), Kennett (1966), Jenkins (1967) and Gibson

FIGURE CAPTION

FIGURE 38

Bathymetric chart of the continental shelf and slope off southern Hawkes Bay showing position of rock samples. Depths are in metres.

Inset: Map of New Zealand showing position of bathymetric chart.

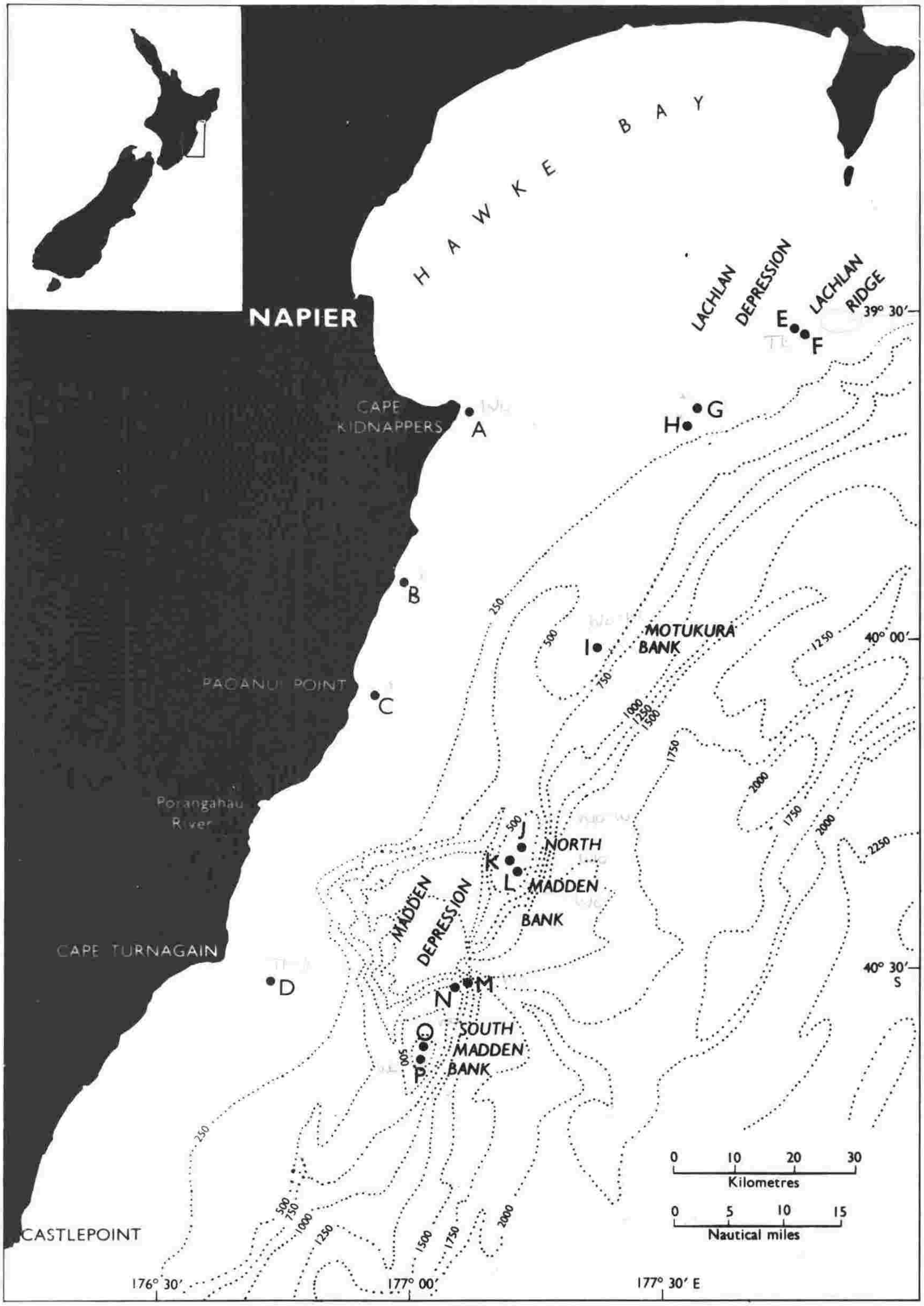
HAWKE BAY
NAPIER
CAPE KIDNAPPERS
PAOANUI POINT
Porangahau River
CAPE TURNAGAIN
CASTLEPOINT
LACHLAN DEPRESSION
LACHLAN RIDGE
MOTUKURA BANK
NORTH MADDEN BANK
MADDEN DEPRESSION
SOUTH MADDEN BANK
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
39° 30′
40° 00′
40° 30′ S
176° 30′
177° 00′
177° 30′ E
250
500
750
1000
1250
1500
1750
2000
2250
0 10 20 30
Kilometres
0 5 10 15
Nautical miles

Fig. 38

(1967). The depths at which the benthonic foraminifera lived were estimated from data recorded by Vella (1957, 1962a, b, 1963), Kennett (1966), Eade (1967) and Lewis (1971). Although the samples were washed thoroughly before foraminifera were extracted some faunas from the samples contain clean specimens which are considered to be Late Quaternary in age.

Listed for each station are the N.Z. Oceanographic Institute station number, the latitude, longitude, depth in metres, gear used to collect the sample and description of the sample.

SAMPLES FROM THE INNER SHELF

A F646 39°39.0'S 177°06.4'E 15m
Short Corer. Few fragments of grey mudstone - similar to Opoitian mudstone on adjacent shore.

B F663 39°55.0'S 177°58.0'E 18m
Orange-peel grab. Limestone covered with worm tubes.

C F698 40°06.2'S 176°55.9'E 51m
Orange-peel grab. Fragments of hard yellowish

grey mudstone - similar in appearance to Miocene rocks on adjacent shore.

D F866 40°33.0'S 176°42.3'E 83m

Pipe dredge. Pale grey mudstone with lumps of chert from side of Turnagain Banks. Mudstone with *Pholadidea*-borings and *Pholadidea tridens* (Grey) present *in situ*. Mudstone contains less than 1% sand-sized grains which are mainly foraminifera.

Fossil foraminifera include specimens of *Astrononion parki* Hornibrook, *Bolivina plicatella* Cushman, *Bolivinita compressa* Finlay, *Bolivinita pliozea* Finlay, *Brizalina* cf. *cacozela* (Vella), *Bulimina senta* Finlay, *Cibicides robertsonianus* (Brady), *Cibicides temperata* Vella, *Gaudryina fenestrata* Finlay, *Globigerina bulloides* d'Orbigny, *Globigerina nepenthes* Todd, *Globorotalia conomiozea* Kennett, *Globorotalia miozea* s.l. Finlay, *Haeuslerella* cf. *morgani* (Chapman), *Lenticulina dicampylus* (Franzenau), *Melonis maoricum* (Stache), *Melonis pompiliodes* (Fichtel and Moll), *Nodosaria* spp. *Nonionellina flemingi* (Vella), *Notorotalia clathrata* (Brady), *Notorotalia taranakia* Vella, *Orbulina universa* d'Orbigny, *Oridorsalis tenera* (Brady), *Pullenia bulloides* (d'Orbigny), *Stilostomella* spp. *Textularia miozea* Finlay, *Textularia* sp. *Uvigerina* c.f. *pygmea* d'Orbigny.

The association of *Textularia miozea*, *Bolivinita compressa* and *Globorotalia conomiozea* is indicative of an Upper Tongaporutuan or Kapitean (Uppermost Miocene) age for the sample. The rest of the fauna is consistent with this age.

The minimum depth at which the sample could have been deposited is 1700m because *Melonis pompiloides* is not found at depths of less than 1700m in Recent sediments. *Cibicides robertsonianus*, *Lenticulina dicampylus* and *Notorotalia taranakia* are also considered to be deep bathyal species.

SAMPLES FROM RIDGES ON THE LACHLAN ANTICLINE

Lachlan Ridge:

E F640a 39°33.0'S 177°44.2'E 124m

Short corer. Grey mudstone with less than 1% sand-sized grains which include detrital grains, foraminifera and volcanic ash.

The mudstone yielded the following fossil foraminifera:

Astrononion parki Hornibrook, *Bolivinita pohana* Finlay, *Bolivinopsis cubensis* (Cushman & Bermudez), *Ceratobulimina kellumi* Finlay, *Cibicides robertsonianus* (Brady), *Cibicides temperata* Vella, *Cibicides* sp., *Ehrenbergina* aff. *mestayeri* Cushman (ventral side higher and less spinose than Recent form - may be an ecological variant), *Globigerina woodi* Jenkins, *Globocassidulina canalisuturata* Eade, *Globoquaderina dehiscens* (Chapman, Parr & Collins), *Globorotalia miozea* s.l. Finlay, *Gyroidinoides subzelandica* Hornibrook, *Lenticulina* spp. *Nonionella malnalingua* Finlay, *Sigmoilopsis* aff. *schlumbergeri* (Silvestri), *Stilostomella* spp. *Trifarina bradyi* Cushman.

The association of *Bolivinita pohana* and *Globoquadrina dehiscens* indicates a Tongaporutuan (Upper Miocene) age for the sample. The rest of the fauna is consistent with this age.

The presence of *Sigmiolinopsis* aff. *schlumbergeri* suggests depositional depths in excess of 1200m. The presence of *Cibicides robertsonianus* also suggests deep water. Large numbers of *Ehrenbergina* aff. *mestayeri* and *Globocassidulina canalisuturata* suggest initial depositional depths of less than 700m but these specimens may have grown in shallow water, have been transported downslope and been deposited in deep water.

F F640b 39°33.0'S 177°44.2'E 130m

Pipe dredge. Hard brown and grey mudstone.

G Z406 39°38.0'S 177°34.0'E 135m

Dredge. Brownish-grey sandy mudstone.

H F642b 39°39.5'S 177°34.0'E 126m

Short corer. Hard grey mudstone.

Motukura Bank:

I F862 40°02.0'S 177°22.2'E 625m

Pipe dredge. Fragments of crumbly grey mudstone in firm plastic grey mud.

Washed samples contain abundant Recent foraminifera including *Loxostomium karrerianum*, and some specimens which are regarded as fossil. The supposed fossils foraminifera include specimens of: *Bolivinita grant-taylori* Vella, *Bolivinita pliozea* Finlay, *Bulimina acealeata* d'Orbigny, *Cassidulina carinata* Silvestri, *Cibicides* sp. *Euuvigerina* cf. *miozea* Finlay, *Globigerina bulloides* d'Orbigny, *Globigerina pachyderma* (Ehrenberg), *Globorotalia tosaensis* Takayana & Saito, *Nonionella magnalingua* Finlay, *Notorotalia* cf. *hurupiensis* Vella, *Notorotalia tarankia* Vella, *Orbulina universa* d'Orbigny, *Siphonaperta macbethi* Vella, *Trifarina ensuriens* (Hornibrook), *Turborotalia inflata* (d'Orbigny).

The association of *Bolivinita pliozea*, *Globorotalia tosaensis*, *Notorotalia hurupiensis* and *Notorotalia taranakia* suggests an Opoitian or Waipipian

(Pliocene) age for the sample.

The presence of Bulimina aceuleata, Nonionella magnaligua, Notorotalia taranakia and Uvigerina pygmea suggests that the mudstone was deposited at depths greater than 200m. The absence of very deep-water species may indicate a depth of deposition of 200-1200m, that is, not necessarily deeper than the depth from which the mudstone was dredged.

North Madden Bank:

J F860 40°20.2'S 177°12.5'E 311m

Short corer. Hard grey mudstone containing about 2% sand-sized grains which are mainly foraminifera.

The fossil foraminifera extracted from the sample include:

Astrononion novozelandicum Cushman & Edwards, Bolivinita compressa Finlay, Bolivinopsis cubensis (Cushman & Bermudez), Bolivina robusta Brady, Bulimina aculeata d'Orbigny, Cassidulina carinata Silvestri, Cibicides *robertsonianus* (Brady), *Cibicides* cf. *victoriensis* Chapman, Parr & Collins (large form), *Ehrenbergina aspinosa* Parr, *Ehrenbergina* aff. *mestayeri* Cushman (thicker and less spinose), *Euuvigerina miozea* (Finlay), *Globigerina bulloides* d'Orbigny, *Globocassidulina canalisuturata* Eade, *Hoegludina elegans* (d'Orbigny), *Marginulina* sp., *Notorotalia kingmai* Vella, *Notorotalia taranakia* Vella, *Orbuline universa* d'Orbigny, *Osangulara bengalensis* (Schwager), *Pullenia bulloides* (d'Orbigny), *Pullenia quinqueloba* (Suess), *Rectobolivina* sp., *Sigmoilopsis* aff. *schlumbergeri* (Silvestri), *Siphonina australia* Cushman, *Siphotextularia* sp., *Stilostomella* spp., *Subbotina* sp., *Turborotalia inflata* (d'Orbigny).

The association of *Bolivinita compressa*, *Siphonina australis*, *Notorotalia kingmai*, *Cibicides* cf. *victoriensis* and *Turborotalia inflata* indicates an Opoitian or Waipipian (Pliocene) age for the sample.

The presence of *Osangularia bengalensis* and

Sigmiolinopsis aff. schlumbergeri suggest that the mudstone was deposited at depths of more than 1200m. The large number of Ehrenbergina aff. mestayeri and Globocassidulina canalisuturata would have lived at depths of less than 500m but may have been transported into deeper water.

K B901a 40°21.0'S 177°11.4'E 196m

Orange-peel grab. Fragments of grey calcareous mudstone riddled with Pholadidea-borings. Mudstone contains 30% carbonate and 2% sand-sized grains which are mainly foraminifera.

Although an effort was made to wash sediment from the borings before attempting to extract fossil foraminifera the sample contained many clean fresh foraminifera which are probably Recent or Sub-Recent. The supposed fossil specimens belong to the following species:

Bulinina rostrata Brady, Cibicides aff. deliquatus Finlay, Ehrenbergina aff. mestayeri Cushman (thicker and less spinose), Euuvigerina miozea Finlay, Globocassidulina canalisuturata Eade, Globorotalia miozea s.l. Finlay, Globo-

rotalia puncticulata, *Gyroidina prominula* (Stache), *Hopkinsina mioindex* Finlay, *Lenticulina vortex* (Fichtel and Moll), *Notorotalia* aff. *biconvexa* Hornibrook, *Trifarina ensuriens* (Hornibrook).

The association of *Globorotalia miozea*, *Hopkinsina mioindex* and *Globorotalia puncticulata* suggests a Lower Opoitian (Lower Pliocene) age for the sample. *Notorotalia biconvexa* is typical of the Southland (Lower Miocene) Series but may have survived until Opoitian times.

The presence of *Bulimina rostrata* indicates depositional depths in excess of 1000m but, as with samples described above, the presence of *Ehrenbergina* aff. *mestayeri* and *Globocassidulina canalisuturata* is anomalous.

L B901b 40°21.0'S 177°11.4'E 188m

Orange-peel grab. Grey calcareous mudstone with *Pholadidea*-borings.

Supposed fossil foraminifera extracted from the sample are:

Cibicides sp., *Ehrenbergina* aff. *mestayeri* Cushman (thicker and less spinose) *Globigerina bulloides* d'Orbigny, *Globocassidulina canalisuturata* Eade, *Globorotalia miozea* s.l. Finlay, *Globorotalia puncticulata*, *Globorotalia sphaericomiozea* Walters, *Lenticulina* cf. *gibba*, *Orbulina universa* d'Orbigny, *Pullenia quinqueloba* (Reuss.), *Sigmoilopsis* aff. *schlumbergeri* (Silvestri), *Siphonina australis* Cushman, *Sphaeroidinellopsis seminulum* (Schwager), *Stilostomella* sp., *Trifarina ensuriens* (Hornibrook).

The association of *Sphaeroidinellopsis seminulum*, *Globorotalia miozea* s.l., *Globorotalia sphericomiozea* and *Globorotalia puncticulata* suggest a Lower Opoitian (Lower Pliocene) age for the sample.

Sigmoilopsis aff. *schlumbergeri* usually occurs at depths of more than 1200m and *Ehrenbergina mestayeri* and *Globocassidulina canalisuturata* at depths of less than 700m.

South Madden Bank:

M F857 40°31.0'S 177°00.0'E 1041m

Pipe dredge. Lumps of grey mudstone.

Supposed fossil foraminifera extracted from the sample are:

Astrononion parki Hornibrook, *Bolivinita granttaylori* Vella, *Bolivinita pliozea* Finlay, *Bulimina rostrata* Brady, *Cibicides inhungia* Finlay, *Euuvigerina miozea* Finlay, *Globigerina bulloides* d'Orbigny, *Globocassidulina producta* (Chapman & Parr), *Globorotalia miozea* s.l. Finlay, *Globorotalia puncticulata*, *Globorotalia tosaensis* Takayanagi & Saito, *Karreriella* c.f. *cylindrica* (Finlay), *Laticarinina altocamerata* (Heron-Allen & Earland), *Melonis pompiloides* (Fichtel & Moll), *Notorotalia taranakia* Vella, *Notorotalia finlayi* Vella, *Notorotalia* aff. *profunda* Vella, *Oridorsalis tenera* (Brady), *Osangularia bengalensis* (Schwager), *Plectofrondicularia pellucida* Finlay, *Pullenia bulloides* (d'Orbigny), *Pullenia quinqueloba* (Reuss), *Sigmoilopsis* schlumbergeri (Silvestri), Stilostomella sp.

The association of Astrononion parki, Cibicides inhungia, Globorotalia miozea, Globorotalia tosaensis, Karreriella cf. cylindrica, Plectofrondicularia pellucida and Globorotalia puncticulata indicates an Opoitian (Lower Pliocene) age for the sample.

The association of Melonis pompiloides, Osangularia bengalensis and Sigmiolopsis schlumbergeri is proof of deposition at depths of more than 1700m.

N B900 $30^{\circ}31.2'$S $177^{\circ}05.4'$E 1280m

Short corer. Few small fragments of grey mudstone.

O B153 $40^{\circ}38.2'$S $177^{\circ}01.6'$E 170m

Cone dredge. Grey mudstone pebbles with pholadidea borings.

The foraminiferal fauna was described by Dr N.deB. Hornibrook in a personal communication to Dr H.M. Pantin dated 14th October 1959 and modified 4th April 1971.

The following fossil foraminifera were identified:

Bolivina affiliata Finlay, *Ehrenbergina fyfei* Finlay, *Euuvigerina notohispida* (Finlay), *Euuvigerina* aff. *pliozea* (Vella), *Globigerina apertura* Cushman, *Globigerinoides trilobus* (Reuss), *Globorotalia crassiformis* (Galloway & Wissler), *Globorotalia puncticulata*, *Melonis* aff. *simplex* (Karrer), *Mucronina sinalata* (Finlay), *Mucronina* aff. *subtetragona* (Finlay), *Sigmoilopsis schlumbergeri* (Costa).

The above list indicates an Opoitian age for the sample. The presence of *Sigmoilopsis schlumbergeri* suggests that the sample was deposited at depths greater than 1200m.

P B892 40°38.8'S 177°01.0'E 128m

Short corer. Crumbly grey mudstone.

The washed sample contained an abundance of clean Recent foraminifera. Fossil specimens were ascribed to the following species:

Astrononion sp. (compressed), *Brizalina* aff.

cacozela Vella, *Bulimina rostrata* Brady, *Cibicides temperata* Vella, *Ehrenbergina* aff. *mestayeri* Cushman (thicker and less spinose), *Globocassidulina canalisuturata* Eade, *Globorotalia puncticulata*, *Hoeglundina elegans* (d'Orbigny), *Lenticulina dicampylus* (Franzenau), *Melonis maoricum* (Stache), *Osangularia bengalensis* (Schwager), *Pullenia bulloides* (d'Orbigny), *Pullenia quinqueloba* (Reuss), *Stilostomellina* spp. *Siphonina australia* Cushman, *Trifarina bradyi* Cushman.

The sample contains a fossil fauna similar to others that are dated as Opoitian (Lower Pliocene) in age.

The presence of *Osangularia bengalensis* suggests that the sample was deposited in water more than 1200m deep. As in other samples from the offshore banks the occurrence of numerous *Ehrenbergina* aff. *mestayeri* and *Globocassidulina canalisuturata* is anomalous.

CONCLUSIONS

1. Mudstones and limestones on the inner shelf are similar to rocks on the adjacent coast. Mudstone from the banks off Cape Turnagain is Upper Miocene in age.

2. All samples from ridges on the Lachlan Anticline are mudstone. The two northernmost samples are Eocene in age. Other dated samples are Upper Miocene or Pliocene in age.

C A F.
Not plotted

3. At some places on the Lachlan Anticline and on the inner shelf the inferred depth at which Miocene and Pliocene benthonic foraminifera lived is considerably greater than the depth from which they were collected (Table 8). The post-depositional history of Miocene sediments has included nett uplift of as much as 1600m.

4. Upper Miocene and Pliocene mudstones from banks on the Lachlan Anticline contain less than 10% of sand-sized grains and are, therefore, unlike Recent bank sediments, which contain a high

TABLE 8

A comparison of depths from which samples were collected and inferred minimum depth of deposition, which is taken at the minimum recorded depth of deep water species of benthonic foraminifera.

Sample	Position	Depth of Collection	Minimum Depth of Deposition
D	Turnagain Banks (inner shelf)	83m	1700m
E	Lachlan Ridge	124m	1200m
I	Motukura Bank	625m	200m
J	North Madden Bank	311m	1200m
K	" " "	196m	1000m
L	" " "	188m	1200m
M	South Madden Bank	1041m	1700m
O	" " "	170m	1200m
P	" " "	128m	1200m

proportion of sand-sized foraminifera, shell, volcanic ash and glauconite (Lewis, in press c). It is inferred that the mudstones were deposited before the Lachlan Anticline began to grow. Similarly mudstones from the inner shelf are unlike Recent shelf sediments which contain a relatively high proportion of detrital sand and the shore line has moved to its present position since Miocene times. Thus the present regime of folding on the shelf and upper slope is post-Miocene in age.

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PAPER 6

WAIMIHIA ASH AND RATES OF SEDIMENTATION ON CONTINENTAL SLOPE RIDGES AND DEPRESSIONS OFF HAWKES BAY.

To be combined with geochemical data by B.P. Kohn for publication in <u>N.Z. Jl Geol. Geophys</u>.

ABSTRACT

Ash of the Waimihia Formation, which was erupted from the Taupo volcanic centre about 3.4 thousand years ago, is identified in piston cores from the continental slope off Hawkes Bay Land District and rates of sedimentation are estimated from the thickness of overlying sediment. The rates range from 0 to 3.6 m/thousand years.

In synclinal depressions on the continental slope, sediment above and below the Waimihia ash consists of thick layers of mud separated by thin sandy layers, some of which contain shallow water foraminifera. The sandy layers are considered to have been deposited by turbidity currents and a maximum of eight of them overlie the Waimihia ash.

Coarse sand-sized pumice that contaminates the mud above the Waimihia ash may represent the Taupo eruption of 1.8 thousand years ago and a deeply buried ash is tentatively attributed to the Oruanui eruptions of 20 thousand years ago.

INTRODUCTION

The Waimihia Formation is the thickest of several Holocene volcanic ashes found in Hawkes Bay Land District. Near Napier it is 0.30 m thick whereas other Holocene ashes are less than 0.01 m thick (Vucetich and Pullar 1964). It was erupted about 3.1 - 3.4 thousand years ago from vents believed to have been situated about 25 km southeast of Taupo (Healy 1964). Isopachs show that much of it was blown eastwards to Hawkes Bay Land District. A considerable amount travelled further east and has now been identified in piston cores from the seabed to the east of the Hawkes Bay coast.

On the continental shelf off Hawkes Bay, Holocene rates of deposition have been estimated from the depth of burial of dated seismic reflectors (Lewis, in press). On the continental slope Holocene reflectors are absent but the top of the Waimihia ash is shown to be a convenient horizon from which to calculate rates of deposition.

COLLECTION OF CORES

Eighteen piston cores and seven gravity cores were collected from the continental slope (Table 9, Fig. 39). The piston cores, the longest being 2.8 m in length, were collected in 50 mm internal diameter steel pipes and the gravity cores were collected in similar pipes with plastic liner. All cores were extruded when wet and examined when dry.

DESCRIPTION OF CORES

The cores consist mostly of pale grey mud with conspicuous horizons of white ash and dark sandy mud (Figs 40, 41). Many of the horizons are bedded layers but others are represented only by sediment in burrows. In many cores a simple cycle of layers is repeated with various modifications. The cycle consists of five types of layer (Fig. 42D), from the bottom upwards, 1. dark sandy mud; 2. dark grey mud with large

TABLE 9

Positions of cores from continental slope.

Core No.	NZOI Stn	Latitude S	Longitude E	Depth (m)	Corer type
1	F637	39°41'	177°59'	1010	short gravity
2	F670	39°51'	177°52'	1291	piston
3	F684	40°00'	177°36'	1357	gravity
4	F683	40°08'	177°32'	1646	piston
5	F671	40°02'	177°50'	1169	piston
6	F682	40°13'	177°45'	2127	piston
7	F690	40°19'	177°26'	1726	gravity
8	F721	40°22'	177°16'	1536	gravity
9	F681	40°23'	177°33'	1936	piston
10	F595	40°36'	177°29'	1814	piston
11	F673	40°11'	177°51'	1419	piston
12	F676	40°21'	177°43'	1650	short gravity
13	F680	40°29'	177°39'	1606	piston
14	F674	40°14'	177°54'	2136	piston
15	F679	40°22'	177°65'	2329	piston
16	B885	40°25'	176°56'	1150	piston
17	F597	40°46'	177°18'	2019	piston
18	F596	40°44'	177°25'	2116	piston
19	F594	40°56'	177°14'	2063	piston
20	F593	40°54'	177°28'	2176	piston
21	F592	40°50'	177°42'	2432	piston
22	F678	40°33'	177°50'	2195	short gravity
23	F677	40°44'	177°53'	2012	short gravity
24	F591	40°53'	177°53'	2400	piston
25	F590	40°59'	177°59'	2469	piston

FIGURE CAPTION

FIGURE 39

Chart of the continental slope off Hawkes Bay Land District showing positions of cores. Depth in metres.

Inset: Map of New Zealand showing position of the study area.

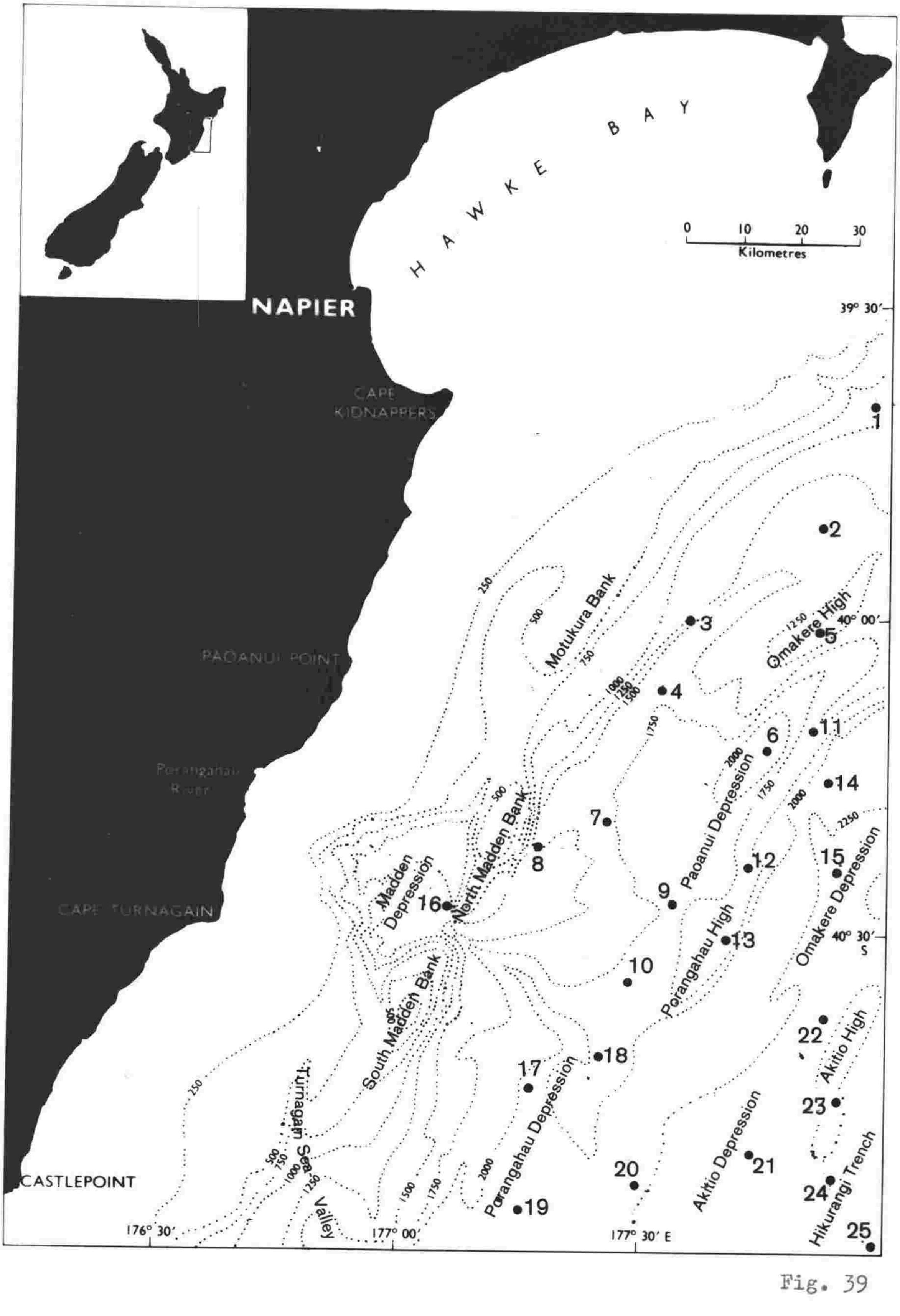
HAWKE BAY
NAPIER
CAPE KIDNAPPERS
PAOANUI POINT
Porangahau River
CAPE TURNAGAIN
CASTLEPOINT
0 10 20 30
Kilometres
39° 30′
40° 00′
40° 30′ S
176° 30′
177° 00′
177° 30′ E
Motukura Bank
Omakere High
Madden Depression
North Madden Bank
South Madden Bank
Paoanui Depression
Porangahau High
Omakere Depression
Porangahau Depression
Turnagain Sea Valley
Akitio Depression
Akitio High
Hikurangi Trench
250
500
750
1000
1250
1500
1750
2000
2250
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

Fig. 39

FIGURE CAPTION

FIGURE 40

Diagrammatic sections of cores from the northern part of the study area showing Waimihia ash (linked by thick broken line). Black is airfall ash, broken line is muddy ash, white is detrital mud and sand, 1 = dark sandy layer, 2 = dark grey sand with either no burrows or large burrows, 3 = dark grey mud with small burrows grading up to 4 = pale grey mud. p = pumice in mud, a = ash. Scales show depth in core in metres and rates of deposition of sediment overlying Waimihia ash from depth to Waimihia ash. W = identified as Waimihia Formation by geochemical techniques (without circle is tentative (B. Kohn).

Fig. 40

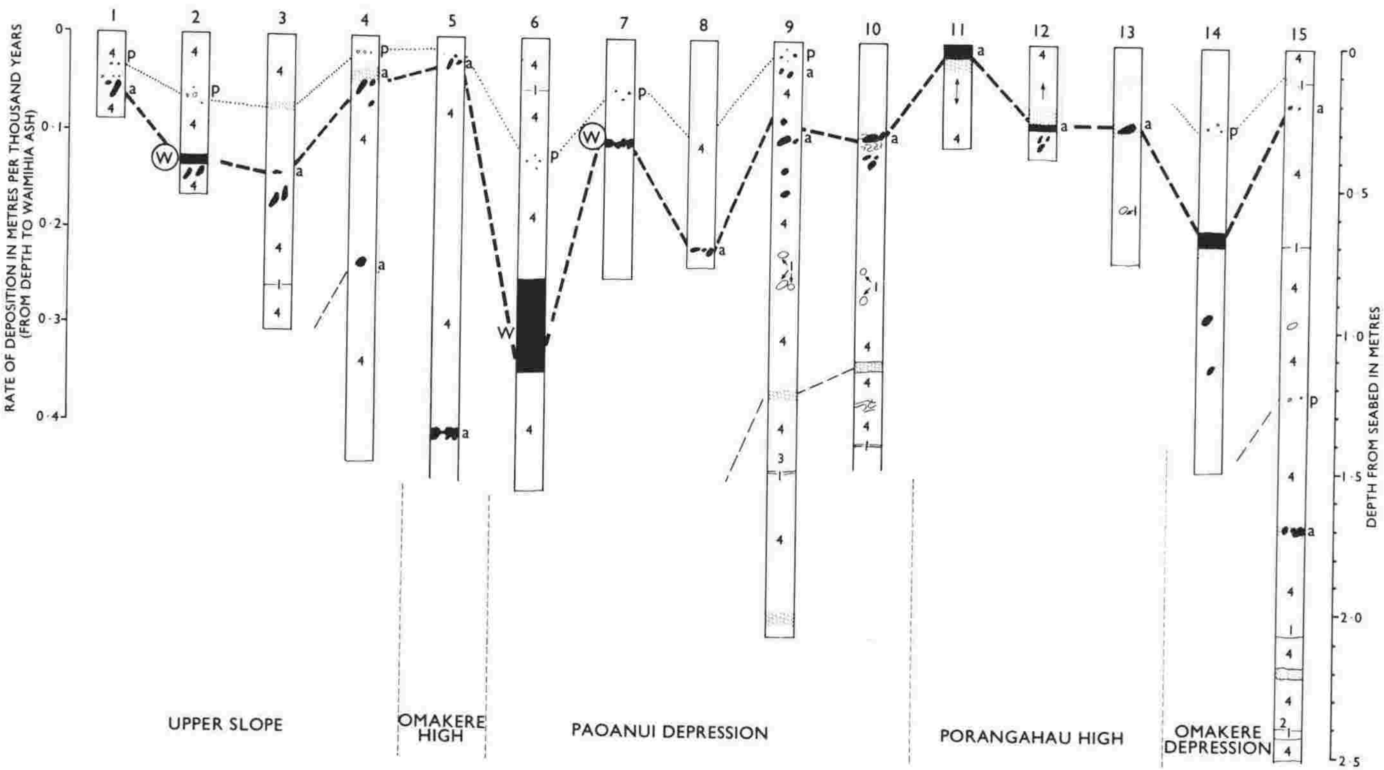
RATE OF DEPOSITION IN METRES PER THOUSAND YEARS
(FROM DEPTH TO WAIMIHIA ASH)
0
0·1
0·2
0·3
0·4
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
W
p
a
DEPTH FROM SEABED IN METRES
0
0·5
1·0
1·5
2·0
2·5
UPPER SLOPE
OMAKERE HIGH
PAOANUI DEPRESSION
PORANGAHAU HIGH
OMAKERE DEPRESSION

FIGURE CAPTION

FIGURE 41

Diagrammatic sections of cores from southern part of study area where turbidites (1, 2, 3) are common. Notations similar to Fig. 40. Percentages to left of each section are percentages of sediment coarser than 0.064 mm. Z indicates those analysed samples with significant proportion of shallow water foraminifera in the sand fraction.

Fig. 41

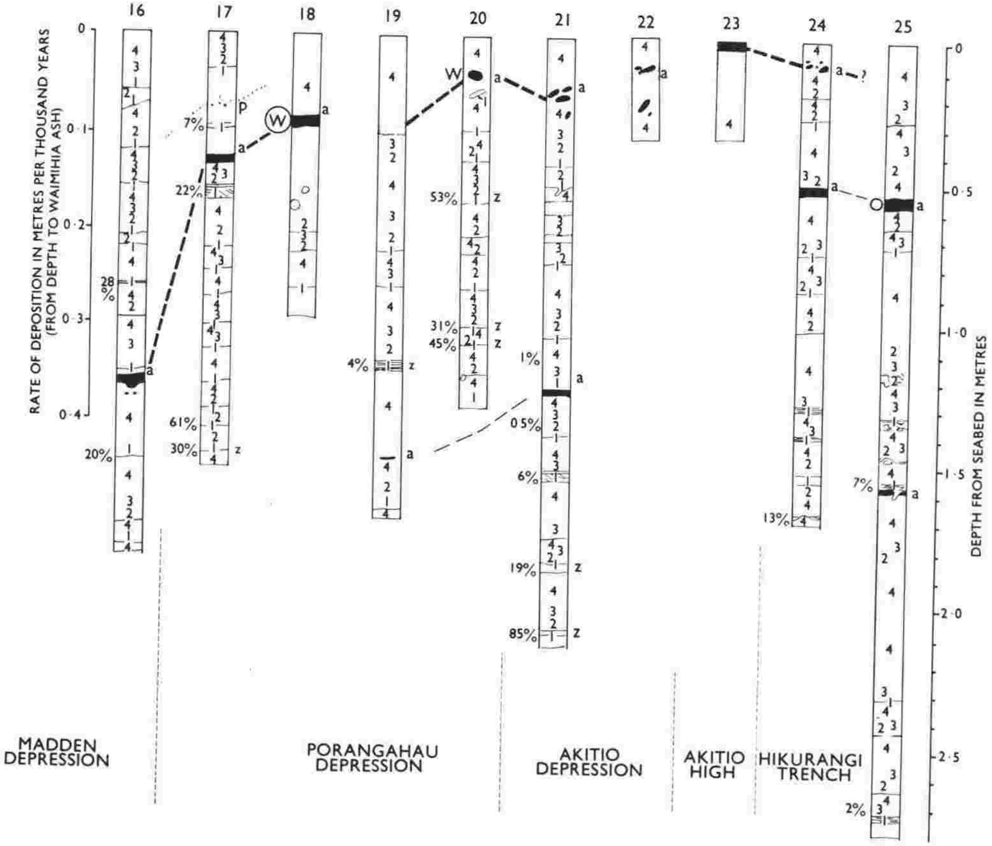
16
17
18
19
20
21
22
23
24
25
RATE OF DEPOSITION IN METRES PER THOUSAND YEARS (FROM DEPTH TO WAIMIHIA ASH)
0
0·1
0·2
0·3
0·4
DEPTH FROM SEABED IN METRES
0
0·5
1·0
1·5
2·0
2·5
W
a
p
z
28%
20%
7%
22%
61%
30%
4%
53%
31%
45%
1%
05%
6%
19%
85%
13%
7%
2%
MADDEN DEPRESSION
PORANGAHAU DEPRESSION
AKITIO DEPRESSION
AKITIO HIGH
HIKURANGI TRENCH

FIGURE CAPTION

FIGURE 42

Photographs showing segments of cores.

A: Core 6, at depth in core of 0.82 - 1.20 m, showing bedding, including graded bedding, in thick layer of Waimihia ash.

B: Core 17, at depth in core of 0.56 - 0.60 m, showing parallel and current bedding in sandy layer.

C: Core 20, at depth in core of 1.09 - 1.23 m, showing parallel and contorted bedding in sandy layer; below sandy layer is pale grey mud, above sandy layer is dark mud with small (and large) burrows.

D: Core 22, at depth in core of 1.13 - 1.41 m, showing ideal cycle of sedimentation; from base, 1 = sandy layer, 2 = dark grey mud with large burrows, 3 = dark grey mud with small burrows, 4 = pale grey mud, a = ash; there is a similar cycle without 2 above the ash.

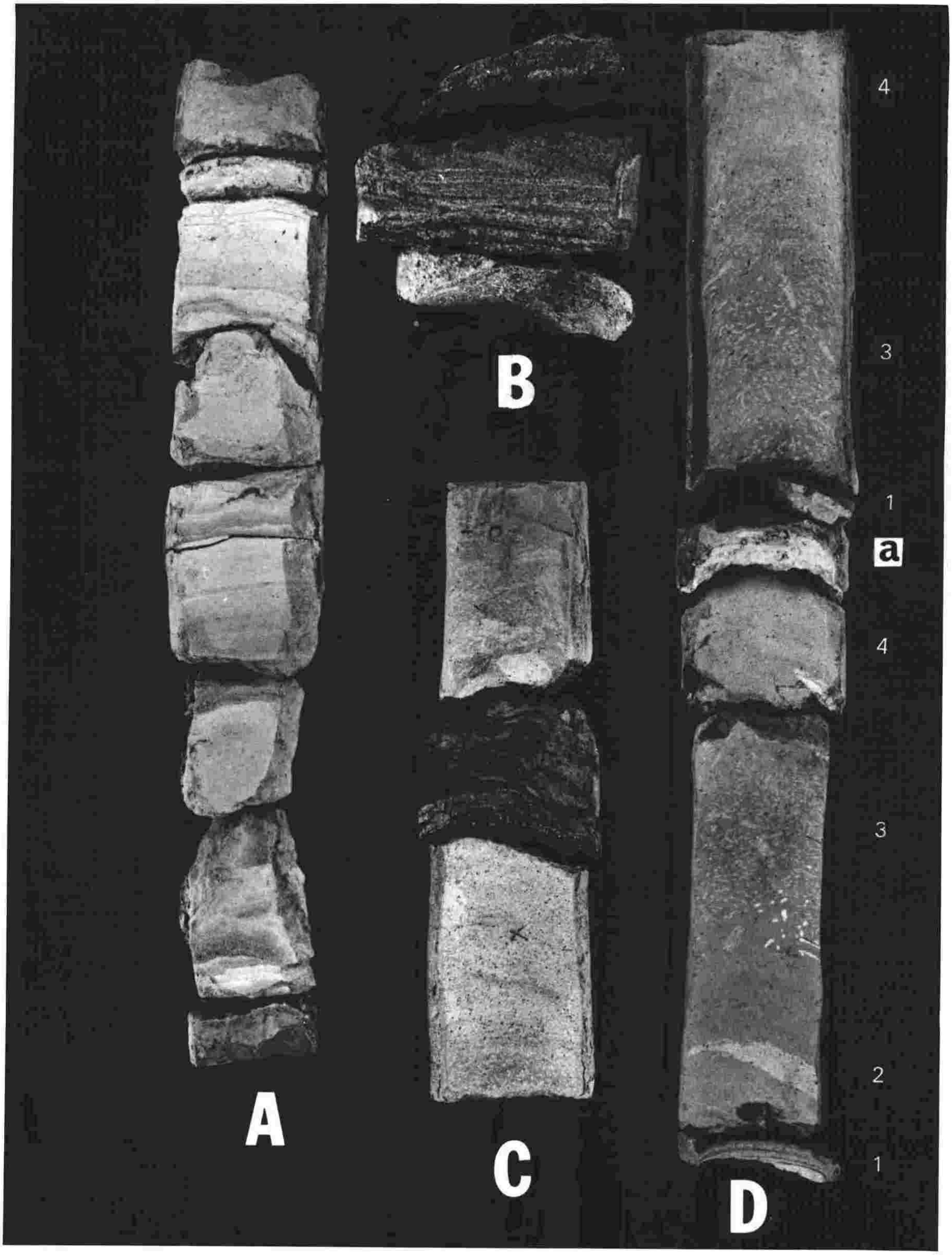

Fig. 42

burrows; 3. dark grey mud with small burrows; 4. pale grey mud; 5. volcanic ash. One or more of the types may be absent because burrowing is rare at some places and volcanic ashes occur in only a few cycles. In the northern part of the study area, sandy layers are rare. In the southern part they are common only in depressions that are downslope from the steep channels on the upper continental slope of the Porangahau River.

Dark sandy mud occurs generally in distinct layers, and only rarely in burrows. Sandy layers have sharp upper and lower boundaries and range in thickness from a 1 mm lamina to a 50 mm thick bed. Many have relatively coarse grains near their base (Fig. 42B, C) but are not evenly graded. All are at least partly parallel bedded and several are partly current bedded (Fig. 42B). The upper part of one layer shows contorted bedding (Fig. 42C) but it may have been disturbed during collection of the core. The proportion of sand-sized grains in samples from 20 sandy layers ranges from 4 to 84% but most sandy layers contains 10 to 50% sand grains. Most of the sand grains are sub-angular detrital quartz and feldspar, and a few are dark minerals and foraminifera. Sandy layers that immediately overlie ash contain thin partings and lenticles of ash. Some sandy layers (Fig. 41) contain a foraminiferal fauna that includes a significant proportion of small foraminifera normally living at depths of 0-50 m. The small foraminifera include Zeaflorilus parri and Virgulinopsis turris. The mud fraction in the sandy layers is predominantly coarse or very coarse silt.

Above each sandy layer is a layer of dark grey mud which contains less than 2% sand and 65-75% silt. The lower part of many such layers is either devoid of burrows or contains only a few large burrows filled with pale grey mud. The upper part generally contains numerous small diameter burrows filled with pale grey mud. The dark grey mud grades upwards into pale grey mud.

The pale grey mud, which forms the bulk of each core shows no evidence of bedding and only faint indications of burrowing. Analyses of this sediment type from a few millimetres below the present seabed show that it contains more clay than the dark grey mud, less than 2% sand and only 55-65% silt. Black specks in the pale grey mud appear to be carbonaceous.

There are no more than two white ash horizons in any core, although there is a third light grey muddy ash horizon in some cores. Many cores include pumice fragments in a band about halfway between the top ash and the seabed. In about half of the cores ash horizons are represented by infilled burrows and in the rest by layers, many of which are parallel bedded. One exceptional layer (Fig. 42A) is 0.34 m thick, all others range from 0.02 to 0.05 m in thickness. The exception consists of a basal layer about 0.01 m thick of moderately coarse, white ash and many overlying bands that grade upwards from coarse ash to fine ash. Some of the overlying bands are discoloured by detrital material. The coarse ashes consist mostly of fine sand-sized, clear glass shards and a few euhedral heavy mineral grains. Fine ashes consist almost exclusively of silt-sized shards.

CORRELATION OF THE WAIMIHIA ASH

The ash horizons can be correlated with those in other cores and with dated ash horizons on land.

The core to core correlation is relatively simple where the tephra stratigraphy in each core is the same. The two youngest horizons, a band of pumice-rich mud and an ash below it can be traced over much of the study area (Figs 40, 41), both remaining at similar relative distances below the seabed. At some of the deeper stations there is no pumice and the ash is thin or absent making correlation doubtful.

The 3.4 thousand year old Waimihia ash is the youngest ash that forms a clearly recognisable layer on the adjacent land (Vucetich and Pullar 1964) and is likely to correspond to the highest, well-defined, offshore ash layer, i.e. the one below the pumice-rich mud. This correlation was tested by trace element analysis of titano-magnetite from the ash (Kohn 1970). Ten samples of ash, 8 from the cores and 2 from Holocene beach deposits at Waimarama and Kairakau on the adjacent land were given to Mr B.P. Kohn of Victoria University, Wellington. He was able to extract sufficient titano-magnetite for analysis from eight of the samples and he compared each trace element composition with that of positively identified ashes in the Taupo area. He confirmed (pers. comm. 20-5-71) that five samples, two from the beach deposits and three from the cores are definitely Waimihia ash; two other core samples are probably Waimihia ash and one core sample cannot be correlated geochemically with any ash on land. The five core samples identified as definitely or probably Waimihia ash are all from the upper ash. The sample that could not be identified is from an ash horizon at the deepest station where the Waimihia ash is thought to be absent. This unidentified ash is tentatively correlated with a lower ash that is about 4 - 8 times deeper below the seabed than the Waimihia ash in seven other cores. If rates of sedimentation have been constant then the lower ash is about 4 - 8 times older than the Waimihia ash, that is, 13 - 27 thousand years old. Thus, the lower ash is tentatively correlated with the Oruanui Ash Member which was erupted about 20 thousand years ago and forms the second oldest distinctive ash layer in southern Hawkes Bay Land District. (Vucetich and Pullar 1969).

The pumice-rich mud above the Waimihia ash is similarly estimated to be about 1.7 thousand years old and is correlated with the 1.8 thousand years old Taupo Pumice Formation (Healy 1964).

RATES OF SEDIMENTATION

Rates of sedimentation for the last 3.4 thousand years can be calculated from the thickness of sediment overlying the Waimihia ash. The thickness ranges from 1.21 m in the Madden Depression to 0.06 m in the Hikurangi Trench. The ash is exposed on the highs (Figs 40, 41). Thus late Holocene rates of sedimentation range from 0.36 m/thousand years in the Madden Depression to 0.02 m/thousand years in the Hikurangi Trench and to zero on the highs.

The detrital sediment above the Waimihia ash is generally all pale grey mud except in the Madden Depression and in the Porangahau Depression. In the Madden Depression there are eight sandy layers above the ash, an average of about 2 per thousand years, and dark sand and dark mud constitute about half of the total volume of sediment. In the Porangahau Depression, downslope from the Madden Depression, there are only two sand layers above the Waimihia ash and dark sediments constitute only about one-quarter of the sediment. The most rapid deposition of pale grey mud occurs in the Paoanui Depression where the rate is 0.23 m/thousand years.

AIRFALL ASH, "HEMIPELAGIC" MUD AND TURBIDITES

Sediment may reach the continental slope by any of five main methods: 1. by aeolian transport and subsequent settling through the water column; 2. in suspension in tidal and ocean currents;

3. in diffuse, turbid clouds that move slowly close to the seabed; 4. in dense, turbid clouds, termed turbidity currents, that move rapidly along the seabed; 5. by either organic or inorganic precipitation from seawater.

The Waimihia ash blankets the topography on land and beneath the sea. Unlike all other types of sediment except animal skeletons, it is deposited on submarine highs and in submarine depressions. It is considered to have fallen on the sea and settled through the water column to its present resting place. At places where the ash formed a layer more than about 0.02 m thick, it apparently destroyed the local infauna because the ash is preserved as an undistrubed white layer. At places where the ash was thin, animals mixed it with mud so that white ash is preserved only in burrows. The only evidence of redeposition of the ash is in the Paoanui Depression where it is thick and contains numerous slightly muddy graded beds (Fig. 42A).

The pale grey mud is the type of sediment that is commonly described as "hemipelagic" and is generally supposed to have been transported in the water column by tidal and ocean currents to the site of deposition. In the study area winds are predominantly offshore and may have been a significant transporting agent of mud-sized particles. Both currents and aeolian transport should deposit a "rain" of mud evenly over the whole topography but mud is observed to have been deposited unevenly, more mud being deposited in depressions than on banks. There are two explanations for the scarcity of mud on the banks. Firstly, mud may have reached the banks but been winnowed by currents that increase in velocity as they pass over the banks. Secondly, mud may never have reached the banks. Moore (1970) has shown that hemipelagic-type mud can be transported in diffuse turbid clouds that move slowly downslope close to the seabed. Banks are isolated from such clouds because they stand above the seabed. The diffuse clouds spread out over the flat floors of depressions and deposit an extremely thin veneer of mud which is soon mixed by animals with earlier veneers. Diffuse clouds have been observed from submersibles

(Moore 1970) and it is probable that deposition by this method is almost continuous but slow.

Layers of sandy sediment, some of which are current bedded, indicate that swift flowing currents have crossed the floors of the depressions in the southern part of the study area. These depressions are downslope from the steep, channelled, upper continental slope off the Porangahau River. Such currents have only rarely affected the northern part of the study area where the upper continental slope is smooth and the only channel is on the side of a rocky, ash and shell covered bank. The currents have affected depressions in a zone at right angles to the trend of the continental slope and therefore are unlikely to be deep ocean currents. They have deposited coarse, detrital sediment including tests of shallow water foraminifera, in flat-floored depressions and appear to be correlated with channels that are incised into the outer continental shelf and upper continental slope. Thus, they have the characteristics of turbidity currents (Kuenen 1964).

The dark mud overlying each sandy layer is presumed to represent the fine fraction deposited by each turbidity current. The dark sand and mud deposited by each turbidity current constitute a turbidite, and are sufficiently thick to have buried and destroyed the local infauna, which only recolonised the area after the pale grey mud had begun to bury the turbidite. Small burrowing animals disturbed the top part of each turbidite and a few large animals penetrated deeper. Burrowing animals rarely penetrated through the dark mud to the basal sandy layer so that thin sands, unlike thin ashes, remain as distinct layers.

It is considered that most turbidity currents originated in the steep channels that incise the edge of the continental shelf off the Porangahau River (Fig. 43); a few may have started in the relatively deep and gently sloping Turnagain Sea-Valley. The shelf break off the Porangahau River is about 130 m deep but was only 10-20 m deep during the last period of low sea level (Lewis, in press). Shallow water foraminifera which lived at the shelf break during low sea level are presumed to have been transported with other sediment from near the shelf break and redeposited

FIGURE CAPTION

FIGURE 43

Tracings of echo sounder profiles and continuous seismic profiles across the channels and flat-floored depressions in the southern part of the study area. On left, Turnagain Sea-Valley system. On right, downslope from channels off Porangahau River. Stippled line shows probable course of turbidity currents. Solid lines are seabed, broken lines are subbottom reflectors. Continuous seismic profiles from depths of more than 1000 m are from Houtz et al (1967) and are published with permission of Lamont-Doherty Geological Observatory.

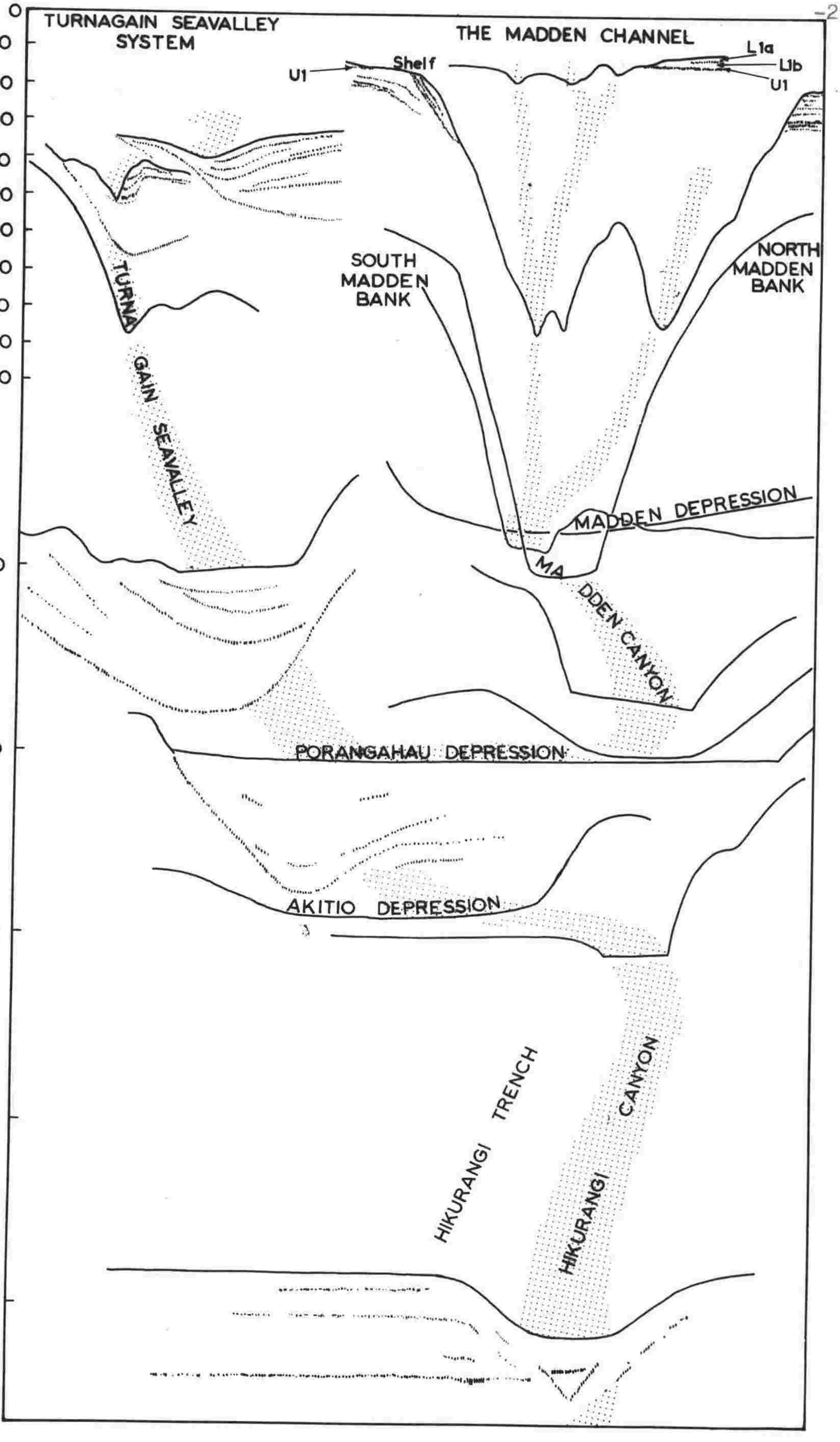
0
100
200
300
400
500
600
700
800
900
1000
1500
2000
2500
3000
3500
TURNAGAIN SEAVALLEY SYSTEM
THE MADDEN CHANNEL
U1
Shelf
L1a
L1b
U1
SOUTH MADDEN BANK
NORTH MADDEN BANK
TURNAGAIN SEAVALLEY
MADDEN DEPRESSION
MADDEN CANYON
PORANGAHAU DEPRESSION
AKITIO DEPRESSION
HIKURANGI TRENCH
HIKURANGI CANYON

Fig. 43

on the lower continental slope. Any turbidity current on the steep upper continental slope off the Porangahau River must necessarily increase its velocity until it reaches the almost flat floor of the Madden Depression at a depth of 1400 m. There it follows a leveed channel. The height from the bottom of the channel to the top of the levee is 120 m. The channel leads to a canyon between the North Madden Bank and the South Madden Bank and a turbidity current with sufficient momentum to cross the Madden Depression descends to the next lowest flat-floored depression, the Porangahau Depression. Since deposition of the Waimihia ash 3.4 thousand years ago, eight turbidity currents have spread over the Madden Depression and two have reached the Porangahau Depression. Prior to 3.4 thousand years ago turbidity currents descended to the Akitio Depression and ultimately to the channelled Hikurangi Trench.

CONCLUSIONS

1. Ash of the Waimihia Formation can be traced more than 100 km seaward off the Hawkes Bay coast.

2. In depressions on the continental slope the Waimihia ash has been buried by pale grey mud at rates ranging from 0.2 to 2.2 m/thousand years.

3. In depressions downslope from the channels off the Porangahau River the ash has been buried partly by pale grey "hemipelagic" mud and partly by dark turbidite layers. Eight turbidite layers overlie the ash in the Madden Depressions where the total rate of deposition is 0.36 m/thousand years and two turbidite layers overlie the ash in the deeper Porangahau Depression.

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PAPER 7

FORAMINIFERA ON THE CONTINENTAL SHELF AND SLOPE OFF SOUTHERN HAWKES BAY, NEW ZEALAND.

For publication in Trans. R. Soc. N.Z.
(Geol.)

ABSTRACT

Foraminiferal populations are described from 29 sediment samples from the seabed off Southern Hawkes Bay Land District, North Island, New Zealand. The samples were collected at water depths ranging from 18m to 2469m, ~~and~~ most of them being of similar volume when wet and representing a similar area of seabed. In each sample the number of specimens, mean width, and weight of each benthonic species is estimated; the number of living specimens is counted and the percentage of planktonic specimens is evaluated. Six biofacies characteristic of the inner (continental) shelf, outer shelf, upper slope, mid slope, lower slope and offshore banks are described.

INTRODUCTION

Despite the potential value of foraminifera for closely defining the environments of deposition of ancient sediments in New Zealand, the environment in which many species of benthonic foraminifera now live and are incorporated into the sediment has been known in only general terms.

Eade (1967) briefly reviewed studies of Recent foraminifera from the seabed around New Zealand and compiled a checklist of Recent New Zealand species. Most studies are either systematic descriptions or lists of species, many from a single sample : distribution studies are rare. Kustanowich (1963) described the distribution of planktonic foraminifera in deep sea sediments and Hulme (1964) gave a detailed account of the variation of shallow water benthonic species in Manukau Harbour. The only distribution study of benthonic species in the open ocean is by Vella (1957) who described the foraminifera of dried dredge samples from Cook Strait and concluded that strong bottom currents had mixed faunas from different depths so that biofacies could not be recognised.

The following investigation is an attempt to quantitatively define the distribution of foraminifera in an area devoid of strong currents and thereby to provide criteria useful for the recognition of specific environments in ancient indurated sediments.

COLLECTION AND PROCESSING OF SAMPLES

Sixteen samples (Table 10, Fig. 44) were collected for detailed quantitative analysis. The two shallowest samples were collected with an orange-peel grab, the remainder with a short gravity corer of 47 mm internal diameter, care being taken with both grab and core samples to prevent washing of the surface sediment (Lewis 1970). The area sampled by the corer was about 1700 mm^2 and a similar area was sampled at the two shallowest stations by pressing a piece of core liner into the surface of each grab sample. The same volume of sediment, 17 ml, representing a layer about 10 mm thick, was removed from the surface of each core and grab sample and preserved with 90% ethyl alcohol.

TABLE 10

Position and depth of 17 ml samples.

Sample	NZOI Stn	Latitude S	Longitude E	Depth	Zone
1	F662	39°49'	177°08'	18m	inner shelf
2	F630	40°37'	176°26.3'	18m	
3	F661	39°50'	177°02.5'	48m	
4	F636	40°38.5'	177°30'	71m	outer shelf
5	F660	39°50'	177°05'	91m	
6	F659	39°50'	177°09'	130m	
7	F861	40°01.5'	177°22'	329m	bank
8	F609	40°45'	176°40'	304m	upper slope
9	F601	40°50'	176°44'	375m	
10	F863	40°02'	177°16.5'	479m	
11	F599	40°52'	176°58'	1240m	mid slope
12	F673	40°11'	177°51'	1419m	
13	F683	40°08'	177°32'	1646m	
14	F679	40°22'	177°55.3'	2329m	lower slope
15	F592	40°50'	177°42'	2432m	
16	F590	40°59'	177°59'	2469m	

FIGURE CAPTION

FIGURE 44

Map of the continental shelf and slope off Hawkes Bay Land District showing positions of 16 samples used for quantitative analysis (numbers) and 13 subsidiary samples (letters). Depths are in metres.

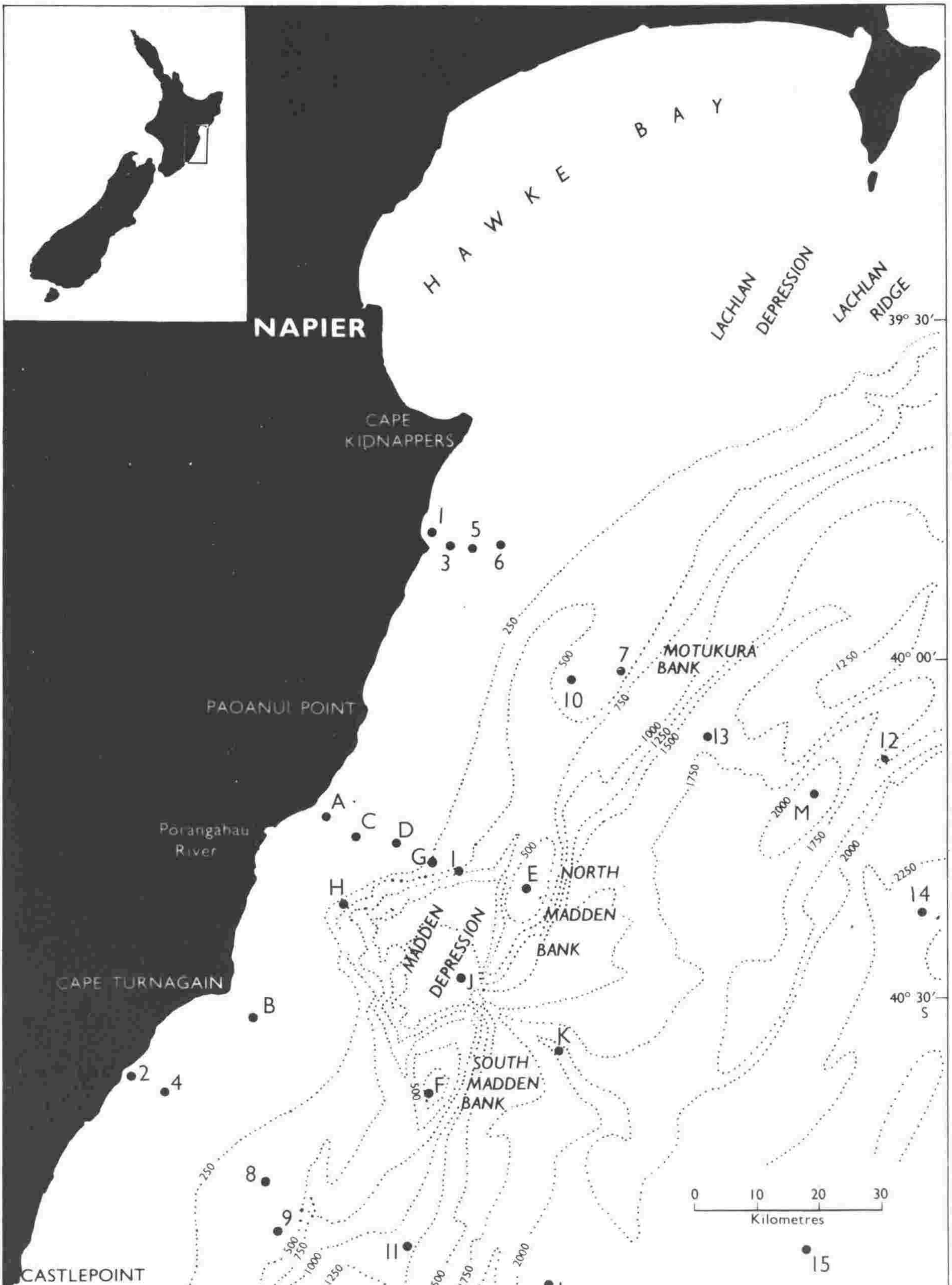
NAPIER
H A W K E B A Y
LACHLAN DEPRESSION
LACHLAN RIDGE
39° 30′
CAPE KIDNAPPERS
1
3
5
6
250
500
7
MOTUKURA BANK
10
750
40° 00′
1250
PAOANUI POINT
1000
1250
1500
13
12
1750
A
C
D
M
2000
Porangahau River
G
I
500
E
NORTH MADDEN BANK
1750
2000
2250
H
14
MADDEN DEPRESSION
J
CAPE TURNAGAIN
B
40° 30′ S
K
SOUTH MADDEN BANK
2
4
F
500
250
8
0
10
20
30
Kilometres
9
500
750
1000
1250
11
1500
1750
2000
15
CASTLEPOINT
L
176° 30′
177° 00′
177° 30′ E
16

Fig. 44

In the laboratory each sample was washed on a sieve with a mesh aperture of 0.06 mm, thereby removing alcohol and all material of silt and clay grade, including some juvenile and small foraminifera. The washed sample was steeped for 12 - 24 hours in Rose Bengal in order to stain protoplasm (Walton 1952) to show which specimens were alive when collected. The stained sample was washed on the 0.06 mm sieve and soaked for 12 - 24 hours in water to remove excess stain from the surface of foraminiferal tests. The sample was then washed through a nest of seven sieves with mesh apertures of 0.050 mm . 0.33 mm, 0.25 mm, 0.17 mm, 0.12 mm, 0.08 mm and 0.06 mm. The sieves sort grains, including foraminifera, according to their width so that foraminifera on the bottom sieve have widths ranging from 0.08 to 0.06 mm.

Each sieve fraction was examined on a water filled counting tray because many fragile specimens are destroyed by drying and because many foraminifera are translucent when wet so that stained protoplasm is easily visible. All benthonic foraminifera on randomly selected squares and the tray were identified and counted until 100-200 specimens had been counted, the total number of specimens in the fraction then being calculated. The percentage of planktonic specimens was determined by counting 100 foraminifera. Each living specimen in the fraction was identified and counted. Thus in each fraction the number of living and dead specimens of each benthonic species is known and the number of planktonic specimens can be calculated. The number in the whole sample was found by adding the numbers in each fraction.

Thirteen subsidiary samples (Table 11, Fig. 44) were collected by similar techniques but the volume of each sample was not accurately measured and stained fractions were examined dry. The presence of living and dead specimens of each benthonic species was noted.

TABLE 11

Position and depth of subsidiary samples.

Sample	NZOI Stn	Latitude S	Longitude E	Depth	Zone
A	B865	40°13.8'	176°48.8'	40m	inner shelf
B	B863	40°31.6'	176°39.5'	42m	
C	B866	40°15.5'	176°54.2'	113m	outer shelf
D	B867	40°16.6'	176°58.2'	186m	
E	B154	40°21'	177°12'	142m	Madden Banks
F	B153	40°37'	177°02'	183m	
G	B868	40°17.8'	177°01.8'	276m	upper slope
H	B881	40°22.0'	176°50.2'	427m	
I	B869	40°19.0'	177°05.6'	625m	
J	B884	40°27.8'	177°03.8'	1439m	mid slope
K	B885	40°35'	177°16'	2028m	lower slope
L	F594	40°56.5'	177°14'	2063m	
M	F862	40°13'	177°45'	2127m	

THE ENVIRONMENT

The sixteen samples for quantitative analysis consist of three samples from each of five depth zones plus a sample from a bank on the upper continental slope (Table 10). The five depth zones are the inner (continental) shelf at depths of less than 50 m, the outer shelf ranging from 50-200 m deep, the upper slope ranging from 200-1000 m deep, the mid slope ranging from 1000-2000 m deep and the lower slope at depths of more than 2000 m.

Previous authors have correlated the distribution of foraminiferal species with the environmental factors, hydrostatic pressure, temperature, composition of substrate, turbulence, light intensity, seawater chemistry, availability of food, and effects of predators (Phleger 1960). Many of these factors are either directly or indirectly related to depth. Hydrostatic pressure increases directly with increase of depth and it is known that the distribution of some marine bacteria is limited by hydrostatic pressure (Oppenheimer and Zobell 1952). The depth of each sample was measured with an echo sounder and values of less than 700 m were corrected with Matthew's (1939) tables (Fig. 45a).

Temperature, at least in a local context, is depth dependent. It was measured on the continental shelf in spring and late summer using a bathythermograph which was allowed to rest briefly on the seabed. Data from the bathythermograph was supplemented by reversing bottle measurements above the continental shelf (Heath 1971) and reversing bottle measurements above the continental slope to the south of the study area (Garner 1961). On the inner shelf the mean annual temperature is about 15°C. and the seasonal variation is about 4.5° (Fig. 45b). Mean annual temperature and seasonal variation decrease with increasing depth so that on the mid and lower slope the temperature is less than 5°C and there is virtually no seasonal variation.

Foraminifera live in and on the surface layer of sediment, whose composition is critical for at least some species. Many fragile species

FIGURE CAPTION

FIGURE 45.

Frequency polygons showing environmental character at 16 stations. A. Depth in metres. B. Temperature in degrees centigrade. C. Percentage by weight of sediment coarser than 0.064 mm. D. Dry weight in grams. E. Estimated rate of sediment deposition in metres per thousand years (from Lewis, 1971)

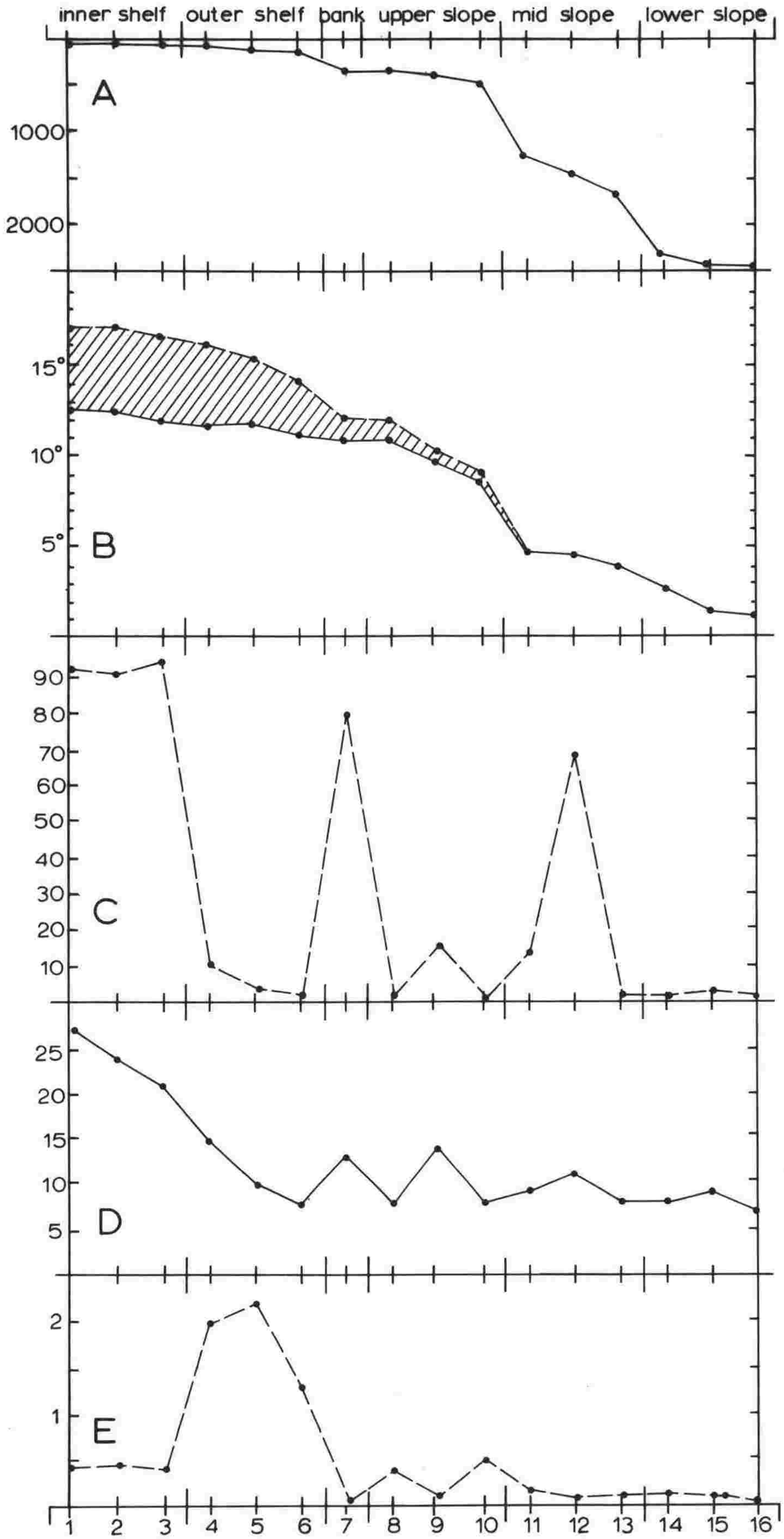
inner shelf
outer shelf
bank
upper slope
mid slope
lower slope
A
1000
2000
B
15°
10°
5°
C
90
80
70
60
50
40
30
20
10
D
25
20
15
10
5
E
2
1
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Fig. 45

could not survive on sand that is subject to continuous movement. Sediment composition in turn affects food supply; muds, at least those that are well oxygenated, might be expected to harbour a richer supply of food than clean sand. The surface 5-10 mm of all mud cores was yellow-brown and presumably well oxygenated, whereas the underlying mud was greenish-grey and presumably a reducing environment. The grain size of the sediment immediately beneath the layer used for foraminiferal analysis was analysed by normal sieving and pipetting techniques. The three samples from the inner shelf are predominantly detrital sand; all other samples contain less than 10% detrital sand (Fig. 45c). In general the sediment becomes finer offshore but samples from banks and local highs on the continental slope contain as much as 70% sand-sized grains, which include foraminifera, glauconite and volcanic ash. Nearshore sands are generally more dense than porous offshore sediments. The dry weight of the nearshore sand is about three times greater than that of the same volume of mud and twice as great as that of the same volume of sediment rich in low density, non-detrital, sand grains (Fig. 45d).

The non-detrital component of the sediment consists of air-fall ash, authigenic minerals, skeletons of animals, including foraminifera, and accumulates relatively slowly on the seabed at most places in the study area. Everywhere except on the slope-banks and highs, the non-detrital component is greatly diluted by mixing with relatively rapidly deposited detrital sediment (Lewis, 1971). The rate of deposition on the middle part of the continental shelf (Fig. 45e) is estimated to range from 1-4 m/thousand years; it is less in very shallow water and near the shelf break (Lewis 1971). In continental slope depressions measured rates range from 0.02-0.35 m/thousand years (Lewis 1971) but rates may be greater in some relatively shallow depressions from which piston cores were not obtained. On continental slope banks rates are less than 0.02 m/thousand years.

DISTRIBUTION OF BENTHONIC SPECIES

The foraminiferal censuses gave the abundance of each species of benthonic foraminifera in the same volume of wet sediment for each station. Walton (1955) pointed out that it is artificial to refer the population to any base other than available living space, and that wet volume is the only natural base for comparison of living marine populations. To compare the results with populations in ancient marine sediments it may be necessary to calculate the number of each species in the same dry weight of sediment using the data in Fig. 45d. The number of specimens in 10 gms of dry sediment is the "foraminiferal number" (Schott 1935; Said 1950).

As the foraminifera were sieved into classes of similar width, the mean width of each species may be estimated from the numbers in each class.

Both the abundance and the mean width may be noted conveniently on logarithmic scales (Table 12). The notations for abundance are the

TABLE 12

Notations for foraminiferal abundance and size.

Notation	Number of Foraminifera in 17 ml of wet sediment	Notation	Mean width from abundance on sieves
-	1	g	greater than 0.50mm
1	2 - 3	f	0.33 - 0.50mm
2	4 - 7	e	0.25 - 0.33mm
3	8 - 15	d	0.17 - 0.25mm
4	16 - 31	c	0.12 - 0.17mm
5	32 - 63	b	0.08 - 0.12mm
6	64 - 127	a	0.06 - 0.08mm
7	128 - 255		
8	256 - 511		
9	512 - 1023		
10	1024 - 2047		
11	2048 - 4095		
12	4096 - 8191		
13	8192 - 16383		
14	16384 - 32767		
15	32768 - 65535		
16	65536 - 131069		

Underlining indicates presence of living specimens.

$\log_2$, rounded downwards, of the number of foraminifera in 17 ml of wet sediment. The notations for mean width represent classes on $\log_2$ (phi) scale (Krumbein 1936), the class boundaries being at $\frac{1}{2}$ phi intervals, the same as the mesh diameters of the sieves.

To assess the relative importance of each species to the accumulation of sediment the mean weight of foraminifera in each class was measured using an electrobalance. The mean was calculated from weights from several different stations, from 10 to 100 specimens being weighed from each station. Table 13 shows weights for various sizes and abundances, the mean weight of a single specimen being shown in the left-hand column. Other columns show the mean weight in each abundance class; the second column being the weight of three specimens, the third the weight of 6 specimens, the fourth the weight of 12 specimens and so on. It is interesting to note that 300-400 small specimens (8a) weigh about the same as a single large specimen (-g).

Table 14 shows the abundance and mean

width of each species at each station and shows, by reference to Table 13, the contribution of each species to the sediment. Abundances range from a single specimen (-) to 80,000 specimens (16). There are about 80,000 specimens of Bolivina robusta at station No. 7. and these 80,000 specimens represent about 100 mgm of a sample that weighs 13 gm. The depth range and abundance of each species are summarised in the following chapter. The presence of living specimens is shown in Table 14 by underlining. Actual numbers of living specimens are not shown because the distribution of living populations is patchy (Eade, in press).

TABLE 13

Weight of foraminifera as a function of size and abundance : letters for size and numbers for abundance as in Table 11. Weights at bottom left are in micrograms, weights in center are in milligrams, weights at top right are in grams.

	-	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
g:	140	420	840	1.6	3.4	6.7	13	27	54	108	215	430	860	1.7	3.6	6.9	14
f:	51	153	306	612	1.2	2.4	4.9	10	20	39	78	157	313	627	1.3	2.5	5.0
e:	20	60	120	240	480	960	1.9	3.8	7.7	15	31	61	123	256	492	984	1.9
d:	7.5	22	45	90	180	360	720	1.4	2.8	5.7	12	23	46	92	192	369	738
c:	2.8	8.4	17	34	67	134	269	538	1.1	2.2	4.3	8.6	17	34	72	138	276
b:	1.0	3.0	6.0	12	24	48	96	192	384	768	1.5	3.1	6.1	12	26	49	98
a:	0.4	1.1	2.3	4.6	9.1	18	36	73	146	292	584	1.2	2.3	4.7	9.7	19	37

TABLE 14

Foraminiferal distribution data, Main part shows abundance and mean width of foraminifera at 16 stations, subsiduary part is a list of stations at which each foraminifera occurs. Underlining indicates presence of living specimens, double underlining indicates presence of more than 20 living specimens.

		inner shelf			outer shelf			bank		upper slope			mid slope			lower slope			
	.	1	2	3.	4	5	6.	7	.	8	9	10.	11	12	13.	14	15	16.	subsiduary
Adercotryma glomeratum	.			.			.		.			.	4a	6a	3b.	3a	1b	2b:	
Alveolophragmium zealandicum	.			.			.		.			-g.			.		-g	-g:	EGH
Ammobaculites filiformis	.			.			.		.			.	1b	3b	2b.		2b	:	
aff. filiformis	.			.			.		.			.	3b	5c	3b.	3b	2b	3b:	JKL
Ammodiscus gullmarensis	.			1c.			.	-a.				.	4c		-c.	3b		:	
planorbis	.			.			.	1d.				.	2f		.	-d		:	DGIL
tenuis	.			.			.		.		-g	-g.			.			:	G
Ammomarginulina cf. ensis	.			.			.	3b.				-b.		8b	5b.	2c		:	IJKL
cf. foliaceus	.			.			.		.	3e	1e	.		4c	.		-d	:	L

	1	2	3.	4	5	6.	7 .	8	9	10.	11	12	13.	14	15	16 .	subsiduary
Ammonia aoteanus	2d	2f	2f	-c	1b												ABDG
Ammoscalaria tenuimargo											1g				1f		
Ammosphaeroidina sphaeroidiniformis							-e	-g		2f	3d	4e	1f	1d	-c		J
Amphicoryna hirsuta							6e			1f							GI
separans				2e													EI
Anomalinoides nipponicus					2b	3c	9b										ACDGHIJ
spherica	-a		2d	6b	2d	2a		1b	-b								AB
sp.	3c		1c					6a	7b	5a	5a			5a	1b		ADIM
Aschemonella catenata																1e	
scabra															2g	1e	J
Astacolus sp.							4d	2c	-c								G
Astrononion novozealandicum	1d	2b		1d	1b	2b	10b	4c	5b	4a	3c		2b				ADGHIK

	.	1	2	3.		4	5	6.		7	.	8	9	10.		11	12	13.		14	15	16	.	subsiduary
cf. tumidum	.				.		$\underline{-b}$		.	8b	.				.		-c		.		1c		:	
Bathysiphon aff. argenteus	.				.				.		.				.	-d	-e		.		$\underline{3b}$		:	KL
globigeriniformis	.				.		1g		.		.			-g	.		$\underline{4g}$	2f	.	2g	2g		:	$\underline{L}$
spp.	.				.				.		.				.		1c	1g	.	$\underline{4d}$	3f		:	$\underline{K}$L
Biloculinella depressa	.				.				.		.		1g		.				.				:	$\underline{B}$EF
Bolivina pseudo-plicata	.	4b		$\underline{3b}$	.		$\underline{4a}$	3a	.		.	$\underline{4a}$	$\underline{6b}$	4a	.	1b	3a	2b	.				:	BCDG
robusta	.	2c	1b		.	3b	1b	-c	.	$\underline{16b}$	.	5c	$\underline{7b}$	$\underline{6b}$	.	5b		2b					:	$\underline{P}$H$\underline{I}$
sphenoides	.				.				.		.		-b		.	$\underline{8a}$	7b	$\underline{5b}$	.	3a	2b		:	
Bolivina? sp.	.				.			2a	.	$\underline{9a}$	.		-b.						.				:	$\underline{B}$CD
Bolivinita quadrilaterata	.			2d	.				.		.			.2d		$\underline{4d}$			.	1d	3c	-d	:	IKM
Brachysiphon corbuliniformis	.				.				.		.				.				.		1g	2g	:	

	.	1	2	3.	4	5	6.	7 .	8	9	10.	11	12	13.	14	15	16	.	subsiduary
Brizalina																			
alata	.			.			.	-c.		1e	.	-d		.				:	J
cacozela	,	-a	2b	1b.	7a	2a	2a.	6a.	1a	1b	2a.	2a		2a.				:	CDGH
earlandi	.			.		2a	.	.		-a	.	-c	5c	3a.	3b	5a	-b	:	LM
spathulata	.	3c	1b	1c.	6b		.	.			.					2a		:	G
aff. subspinescens	.			.			3b.	1b.	4b	5b	.	4c	3b	2b.	1b			:	
Brizalina? kerreriana	.			-d.	7d	6d	6c.	6d.	6c	6b	2c.	-c	-f	.				:	ABCDGHI
Bulimina																			
aceuleata	.			.			.	9d.	5d	9d	6c.	6c	8c	6c.	5d	6d	4d	:	DGIJKLM
marginata	.	2c	1d	-a.	5c	5d	5c.	8c.	6b	6d	2c.			.				:	ACDEGHI
nipponica	.	-d	-e	2c.			.	.	-c	4d	1c.	3d	7d	2e.	2d	1c	1d	:	DGIJKLM
rostrata	.			.			.	.			.	7c	3b	7c.	1c	2d		:	L
Buliminella madagascariensis	.		1c	.			.	.			.			.				:	I
Cancris maoricus	.			.			.	3g.			.			.				:	
Cassidulina carinata	.	3b		2c.	2d	6b	3b.	11b.	5b	9b	5c.	8c	7c	4b.	3b	-c	-b	:	ABDEGHIJM

	.	1	2	3	.	4	5	6	.	7	.	8	9	10	.	11	12	13	.	14	15	16	.	Subsiduary
Chilostomella cushmani	.	1c			.				.	1d	.	6d	5c	3d	.	1d		-f	.				:	CDGHIJKL
cf. oolina	.				.				.		.			5b	.	5d	1d	4c	.	2c	2d	2e	:	
Cibicides ihungia	.				.				.	-d	.	1d	7d	-f	.	1d			.				:	L
marlboroughensis	.	4c	4d	5c	.	-f	2b		.	10e	.	4d	5e	-d	.	1d	3b	-c	.		1d	1e	.	ABDGHIM
wuellerstorfi	.				.				.	6f	.	4d	4e		.	-d	3f	1d	.	2c			:	GL
Cornuspiroides foliaceous	.				.				.		.				.				.				:	GIL
Cribrononion argenteum	.			1d	.	4c	2b	2a	.		.				.				.				:	ACDHI
charlottensis	.	6c	4c	5c	.	1d	3b	3b	.		.				.	1c			.			1d	.	ACD
simplex	.	4c	2c	3c	.	3b			.		.				.	3b			.				:	AIK
Cribrostomoides wiesneri	.			2d	.				.		.				.	-b	5b		.	2b	4b		:	
sp.	.				.	6d	5d	4d	.		.	3c	1d		.				.				:	ACD
Cyclammina cancellata	.				.				.		.			1g	.			4d	.				:	
aff. pusilla	.				.				.		.	1g			.				.				:	

	.	1	2	3	.	4	5	6	.	7	.	8	9	10	.	11	12	13	.	14	15	16	.	Subsiduary
Cystammina pauciloculata	.				.				.		.				.		1c		.	1d	1d	2b	:	
Dentalina cf. caudata	.				.				.	1c	.		-b		.				.				:	G
aff. filiformis	.		-b	1c	.				.		.	1g	1d		.	-b			.				:	CG
subemaciata	.				.				.	5f	.	3d	2f		.	-g	4c		.		2b		:	GI
subsoluta	.				.				.	4f	.			-e	.				.				:	CGI
Disçammina compressa	.				.				.		.								.		2d		:	
Discorbinella cf. bertheloti	.			1c	.				.	8c	.		4c	2c					.				:	ACDG
Discorbis dimidiatus	.	5d	4e	4d				-d	.		.				.				.				:	A
Dyocibiciades primitiva	.	3d	2d	3d	.				.	2f	.				.				.				:	AB
Eggerella bradyi	.				.				.		.				.	4d	7d	3b	.	3c	1b	1f	:	ILM
scabra	.	2c			.				.		.	2d			.		5b	-e	.	-a			:	ADJ
Ehrenbergina mestayeri	.	-d		1d	.				.	-e	.				.				.				:	EF

	.	1	2	3.	4	5	6.	7 .	8	9	10.	11	12	13.	14	15	16	.	Subsiduary
Elphidium novozealandicum	.	3d	3d	3d.	2c		.	.			.			.				:	A
Entolingulina sp.	.			.			.	.			.			.			2g	:	
Epistominella exigua	.	2a	2b	7a.	10a	9a	8a.	6a.	5a	6a	5a.	7a	7a	6a.	5b	7b		:	ACDM
Eponides pusillus	.	-a		1a.			.	11a.	5a	8a	6a.	8a	3a	6a.	6a			:	GHIKM
- tumidulus	.			.			1a.	.			.		4b	2b.				:	
Euuvigerina peregrina	.		-d	.			.	10e.	6f	7e	5e.	7d	6e	2c.	3e	2e	2e	:	ADGIJKLM
Evolvocassidulina orientalis	.	2c		3c.	4c	5c	.	11b.	7b	7b	6b.	-b	1c	3a.		-c		:	ABCDGHI
Fissurina spp.	.	2c	1a	1b.	-b	2b	1b.	5c.	3c	6d	1c.	6c	6d	2d.	3b	4b	2d	:	ABCDGHILM
Florilus scaphum	.			.			.	.			2a.	4a	5b	.				:	

	.	1	2	3.	4	5	6.	7 .	8	9	10	11	12	13.	14	15	16 .	Subsiduary
Fursenkoina rotundata	.			.			.	-c.	1c	3c	4c.	4c	3c	.		-e	.	GI
squammosa	.			.			.	1c.	5c	1c	2a.			.			.	DG
Gaudryina convexa	.			.			.	.			.			.			.	BEF
Gavelinopsis hamatus	.	4b	5c	3d.			.	7b.			.		-d	.			.	AB
lobatulus	.			.			-c.	7a.	4b	5c	3b.	5b	4b	.			.	DG
Glabratella radiata	.	3d	4d	1d.			.	.			.			.			.	
zealandica	.	5c	4c	3d.	-d		.	.			.			.			.	
Globobulimina turgida	.			.			.	1e.	3d	2e	.			.			.	CDG
hoeglundina	.			.			.	6e.		3e	.			.			-d.	GR
notovata	.			.			.	1d.	2e	2c	2d.	1e	5e	1f.	2e	4d	4e.	DG
cf. pacifica	.			.			.	.			.	-d		2d.	1c	3c	.	D
Globocassidulina canalisuturata	.			.			.	10d.			1e.			.			.	EF
aff. inflata	.	1a		.		4a	3a.	9a.			4a.	4a	6a.	4b			.	A

	.	1	2	3	.	4	5	6	.	7	.	8	9	10		11	12	13	.	14	15	16	.	Subsiduary
minuta	.				.				.	8a	.				.		5b	1b	.			1b	.	J
producta	.	1b			.			2a	.	4c	.				.	1b	6c	3b	.	5a	-e	5c	.	
spherica	.	-a		2d	.		-c		.		.				.				.				.	A
Glomospira charoides	.				.				.		.				.		6c		.	2b			.	L
cf. elongata	.				.				.		.				.		1c		.				.	
gordialis	.				.				.		.		-c		.	2c	6c		.	2b		1b	.	DK
Gyroidina orbicularis	.	2c	1b	3d	.			2b	.	7a	.	3a	4c	3b	.	4c	8c	4c	.	3b	3b		.	ADGIKLM
Gyroidinoides neosoldani	.			1d	.				.	-d	.				.	1f	5d		.	2e			.	JKLM
Haplophragmoides canariensis	.	2c			.	1c		2d	.	-c	.				.		-c		.		1c		.	ABC
cf. scitulum	.				.				.		.		3b		.		-b		.				.	IJ
sphaeriloculus	.				.				.		.	-c			.	4b			.			-e	.	DI
subtrullissatus	.				.		3e		.		.		2g	1c	.				.				.	CDJ
trullissatus	.				.				.		.				.				.		1c		.	

	.	1	2	3	.	4	5	6	.	7	.	8	9	10		11	12	13	.	14	15	16	.	Subsiduary
Heterolepa aff. dutemplei	.				.				.	9g	.		1f		.				.				.	DGJ
Hoeglundina elegans	.				.				.		.		1e	1d	.	1e			.		-g	1e	.	CDEH
Hopkinsina pacifica	.				.		4a	3a	.	3a	.	4a	5b	1b	.	4a			.				.	CDGHI
Hormosina globulifera	.				.				.	5f	.		3e		.	2e	3b	2d	.		5c	4c	.	L
Hyperammina friabilis	.				.				.		.				.		-g		.		1f		.	L
Jaculella acuta	.				.				.		.				.				.				.	KL
Karreriella apicularis	.				.				.		.				.	3c	6d		.	3b	1d	1c	.	K
bradyi	.				.				.		.				.		4d		.				.	ILM
Lagena spp.	.			1c	.	5c	2c	3c	.	6d	.	4c	2c	2c	.	3d	5d	3d	.	2b	4b	3b	.	CDGHIM
Lagenammina bulbosa	.				.				.		.				.				.		2b	1b	.	L
difflugiformis	.				.				.		.				.	-b	2c	4b	.	5b	6b	3c	.	L
sp.	.				.				.		.				.			1a	.		3b	1b	.	

	.	1	2	3	.	4	5	6	.	7	.	8	9	10	.	11	12	13	.	14	15	16	.	Subsiduary
Laryngosigma hyalascidia	.				.				.		.				.				.				.	B
Laticarinina altocamerata	.				.				.	5d	.				.		3d	-c	.				.	
pauperata	.				.				.		.				.			3d	.		3b		.	M
Lenticulina spp.	.	-d	-d	2d	.	5b	3e	2d	.	9f	.	4d	5d	3f	.	2d	5d	2a	.	-e	-b		.	ABCDEFGIM
Marginulina glabra	.				.				.	2e	.				.				.				.	M
tenuis	.				.				.	6d	.				.				.				.	G
Marginulinopsis bradyi	.				.				.	1a	.				.				.				.	E
Marsipella elongata	.				.				.		.				.				.		1g		.	
Martinottiella cf. communis	.				.				.		.				.				.				.	GJ
Massilina brodiei	.	1b			.				.		.				.				.				.	A

	.	1	2	3.	4	5	6.	7	.	8	9	10.	11	12	13.	14	15	16	.	Subsiduary
Melonis cf. barleeanum	.			.			.		.			.2a.	5c	5d.	1d.	3b	3c	1c	.	JKLM
sphaeroides	.			.			.		.			.			.			1b.		
Miliolinella subrotunda	.	3c		2d.	2c		.		.			.			.				.	ABEF
Nodosaria calomorpha	.			.			.	-a	.			.	1b		.	1b			.	JM
simplex	.			.			.		.			.			.				.	G
Nonionella bradyi	.			.			.		.		-c	7b.	4a		2b.	4a			.	GKM
aff. translucens	.			.		2d	.		.		-a	.	6a	4a	3a.	7b	7b		.	
turgida	.			3c.	6c	5b	5b.	7b	.	4c	4c	6b.	-a	6b	4a.				.	ACDGHIK
Nonionellina flemingi	.			6b.	8b	7b	7b.	9c	.	5c	8b	6c.	-b	3b	3b.			3b.		ACDHJ
Notorotalia aucklandica	.			.	1e		.		.	-e		.			.				.	A
clathrata	.			.			.		.			.			.				.	AB
finlayi	.			3d.	5c	5d	3d.		.	1c	4e	1d	-c		.				.	ACDGHI

	.	1	2	3	.	4	5	6	.	7	.	8	9	10	.	11	12	13	.	14	15	16	.	Subsiduary
inornata	.		-d		.		-c		.		.			-d	.				.				.	AH
profunda	.			-c	.		-d	1d	.	9f	.	1e	8e	3d	.				.				.	CGI
zelandica	.		4i	1f	.	3d	1f	1g	.	46	.	1f			.				.				.	ACDHI
Oolina spp.	.	2c	2d	2d	.	2c	-c		.	1a	.		-b	2b	.		2b	5d	.	1b			.	ABDGJI
Oridorsalis tenera	.				.	3d	4d	5c	.	11c	.	6c	6d	4c	.	2d	5d	5c	.	4c			.	CDGHIKLM
Orthomorphina georgiana	.	2c		2c	.		1c		.		.				.				.				.	H
Osangularia bengalensis	.				.				.		.				.	5c	6d	-c	.	2b			.	LM
sp.	.				.				.		.				.			2b	.	1c			.	J
Parafissurina spp.	.				.				.		.		-c		.	1c	3b		.		1c	1d	.	BL
Pelosina aff. bicaudata	.				.				.		.				.	1c		2b	.		5b	1b	.	L
didera	.				.				.		.				.			-d	.	-f			.	

	.	1	2	3	.	4	5	6	.	7	.	8	9	10		11	12	13	.	14	15	16	.	Subsiduary
Planodiscorbis rarescens	.				.				.	5e	.		1d		.	-d	1b		.				.	
Planularia tricarinella	.				.				.		.	1f			.				.				.	CDG
Planulina aff. ariminensis	.				.				.	7b	.	1f	1f	-b	.		3c		.				.	
Praeglobobulimina spinescens	.				.			-d	.		.	4d	2c	-d	.		-d		.				.	G
Psammosphaera fusca	.			-e	.				.		.		3e	1f	.	1f	1g		.		1f	1e	.	ACDJIK
parva	.				.				.		.				.	-e			.				.	K
Pseudobolivina sp.	.				.			1b	.		.				.				.				.	D
Pullenia bulloides	.				.				.		.				.	3d	8d	2b	.	2c	3b	1c	.	LM
subcarinata	.	-a		1c	.			1d	.	7d	.	2d	5c	1c	.	4c	6d	1c	.	1d	3b	-d	.	DGIKLM
Pyrgo murrhyna	.				.				.		.		-f		.	-e			.	1f	2f		.	L
pisum	.				.				.	-d	.	-f	-c		.			-d	.				.	E

	.	1	2	3.	4	5	6.	7	.	8	9	10.	11	12	13.	14	15	16	.	Subsiduary
Pyrgoella spherica	.			.			.		.			.			.				.	GI
Quinqueloculina colleenae	.			.			.		.			.			.				.	EF
cooki	.			1e.			.		.			.			.				.	A
incisa	.	3b	1d	2c.			.		.			.			.	-c			.	A
kapitiensis	.	1d		2d.	4b	-a	.		.			.			.				.	ABC
lamarkiana	.		3d	.	1f	1f	.		.			.			.				.	A
aff. lata	.	4c		5c.			.		.			.			.				.	B
neosigmoilinoides	.	4c	5d	4d.	1c	3e	2c.		.		-b	.	-f		.				.	AHJ
suborbicularis	.	1d		2c			.		.			.			.				.	A
triangularis	.	2e		2d.			.	-c.	.	1e		.			.				.	ABE
wiesneri	.			.			.		.		-a	.	-d		.	1.b	5a		.	
cf.venusta	.			.			.		.			.			3a.		4a		.	
Ramulina globulifera	.			.			.	6e	.			-g.			.				.	
Rectobolivina columnellaris	.			.			.	3d	.			.			.				.	

	.	1	2	3.	4	5	6.	7 .	8	9	10	11	12	13.	14	15	16 .	Subsiduary
Recurvoides contortus	.			.			.	.			1f.	1c	5d	1c.		3c	1a.	GIJK
sp.	.			.			.	.				1g		-f.	1g	-f	.	
Reophax bacillaris	.			.			.	.			.			.			.	I
dentaliniformis	.			.			.	.			-a.	3d	4b	3c.	3e	2c	5d.	LM
distans	.			.			.	.			.			.		1g	.	K
guttifer	.			.			.	.	-c		.	-b		.	2e	3d	1d.	JL
aff. guttifer	.			.			.	.			.	4b	4b	-c.		1f	.	IJ
micaceus	.			.			.	.			.			.			2d.	
scorpiurus	.			.	1a	-c	.	.	1d		2d.			.			.	CIJK
subfusiformis	.			.			.	1c .			.			.			.	
spp.	.			.			2b.	.	-f		.	4c	4b	3c.			.	L
Rhabdammina abyssorum	.			.			.	.			.			.			1f.	

	.	1	2	3.	4	5	6.	7	.	8	9	10.	11	12	13.	14	15	16	.	Subsiduary
Rhizammina algaeformis	.			.			.		.			.		2g	4e.	3e	5f		.	L
sp.	.			.			.		.			.	6f	2f	1g.	5f	9f	5d	.	L
Rosalina bradyi	.	6b	3c	5d.	5b		-b.		.			.			.				.	ABDG
irregularis	.	4d	3c	2e.			.		.			.			.				.	AB
paupereques	.			.	1d		.		.			.			.				.	
Saccammina cushmani	.			.			.	5f	.		3e	.	2e	3b	2d.		5c	4c	.	L
sphaerica	.			.			.	-b	.		2f	.	2e	1e	1c.	-g	1d	-g.		J
Saracenaria latifrons	.			.			.	3g	.	-f		.			.				.	DGH
Scutuloris hornibrooki	.			2c.			.		.			.			.				.	K
Seabrookia earlandi	.			.			.	8b	.		1b	-b.		4a	.	3a	2b		.	D
sp.	.			.			.		.			.	2a		.	2a			.	
Sigmoilopsis schlumbergeri	.			.			.		.			.	4d	6d	-c.	2c	-d	-d.		M

	.	1	2	3	.	4	5	6	.	7	.	8	9	10	.	11	12	13	.	14	15	16	.	Subsiduary
wanganuiensis	.				.				.	8c	.				.				.				.	K
Sigmomorphina lacrimosa	.				.				.		.				.				.				.	EF
Siphonaperta crassa	.				.				.		.				.				.				.	DEF
macbethi	.				.				.	4g	.				.				.				.	AB
parvaggluta	.			-b	.				.		.				.				.				.	B
Siphonina cf. tubulosa	.				.				.	8c	.				.				.				.	
Siphotextularia fretensis	.				.				.	9e	.	3e	6e		.	1d	-c		.				.	DEG
aff. fretensis	.				.				.		.				.				.	2c	1d		.	
mestayerae	.				.				.		.				.				.				.	EI
Siphouvigerina asperula	.			1c	.				.	7d	.	-d	3d		.				.		1d		.	DGH
interrupta	.				.				.	10b	.	3c	6b		.	-c			.				.	DGJ
Sphaeroidina bulloides	.	-e			.	1d	2d	6d	.	6e	.	5d	4d	1e	.	3d	4d		.	2d	2d		.	BCDGHJL

	.	1	2	3.	4	5	6.	7	.	8	9	10.	11	12	13.	14	15	16	.	Subsiduary
Spirillina obconica	.			.			.		.			.			.				.	B
vivipara	.			.			.		.			.			.			-c	.	AB
Spiroloculina acutimargo	.		-d	.			.		.			.	-b	1c	.				.	A
Spiroplectammina cf. biformis	.			.			.		.			.	5a	5a	2a.	2a	2b	-d	.	
Stainforthia concava	.			.			.	-a.			1b	2a.	1b	5b	3a.	4a	6b		.	D
sp.	.			.		3a	.		.			.	4a	-b	3b.	3c			.	
Storthosphaera albida	.			.			.		.			.		-g	2b.				.	L
Textularia conica	.			.			.		.			.			.				.	ABCEFH
earlandi	.			.	6b	2b	2a.		.	2a		.	1b	5b	.				.	AI
proxispira	.	1d		.			.		.	2b		.			.				.	BH
aff. sagittula	.			.			.		.			.	-e		-d.				.	F

	.	1	2	3	.	4	5	6	.	7	.	8	9	10	.	11	12	13	.	14	15	16	.	Subsiduary
Thurammina albicans	.				.				.		.				.	-b		4b	.		2d		.	D
castanea	.				.				.		.				.		2d		.			1b	.	
heusleri	.				.				.		.				.				.			2b	.	
Tolypemmina vagans	.				.				.		.				.				.		1e	2e	.	
Trifarina angulosa	.	1b			.			2a	.	10b	.		6b	-c	.	7b	5b	5b	.	3a	3b		.	DGIJKM
bradyi	.		-c		.				.	6d	.			1b	.	1c			.				.	
gracilis	.				.		2b		.		.				.				.				.	A
Triloculina trigonula	.				.				.		.				.				.				.	EF
Tritaxis conica	.				.				.		.				.		1c		.				.	A
Trochammina aff. globigeriniformis					.				.		.				.		5a	2a	.	3a			.	JK
inflata	.				.				.	1a	.		-b	3a	.	1b	-a	3b	.	2a	2b		.	DGIJK
ochracea	.				.	-b	3c	1a	.		.				.				.				.	H
pusilla	.				.	2c	1c	1b	.	1b	.	3c	3c	2a	.	6b	5b	4b	.	4b	6b		.	CDIJ

	.	1	2	3	.	4	5	6	.	7	.	8	9	10	.	11	12	13	.	14	15	16	.	Subsiduary
sorosa	.			$\underline{4a}$	.				.		.	$\underline{2b}$			.				.			4b	.	B$\underline{H}$
squamata	.	$\underline{2b}$		$\underline{1a}$	.	5b		3a	.		.		$\underline{1b}$		.	$\underline{-a}$			.				.	ADH
tasmanica	.			$\underline{\underline{6b}}$	.		$\underline{3a}$	1c	.	1c	.	-c			.	$\underline{2c}$	$\underline{5b}$	2b	.				.	J
sp.	.			$\underline{-a}$	.		$\underline{4a}$		.		.				.				.				.	$\underline{C}$
Valvulineria aff. laevigata	.				.				.		.		3d	$\underline{-a}$	.	$\underline{2b}$	$\underline{5c}$	3b	.	$\underline{1c}$			.	
Virgulopsis turris	.	$\underline{\underline{5b}}$	3b	4b	.	6b	5a	2a	.		.				.				.			-a	.	H
Zeaflorilus parri	.	$\underline{\underline{7c}}$	5d	$\underline{\underline{6c}}$	.	4b	3b		.		.				.				.				.	$\underline{A}$GHI

SYSTEMATIC NOTES ON BENTHONIC SPECIES

NOTE : For synonymies see Eade (1967). Where a reference is given it indicates a figure which is not the original for the species but is considered to represent the same species as the specimens from the study area. Many species are illustrated in Brady's (1884) plates which have been reprinted by Barker (1960).

Order FORAMINIFERIDA

Suborder TEXTULARIINA

Superfamily AMMODISCACEA

Family ASTRORHIZIDAE

Subfamily ASTRORHIZINAE

Rhabdammina abyssorum Sars

Brady 1884, pl. 2, fig. 8.

Remarks: Triradiate tubes, wall of calcareous debris including planktonic foraminifera.

External tube diameter: 0.4 - 0.5 mm.

Depth range: 2469 m, no living specimens.

Occurrence: Rare, only at deepest station.

Rhizammina algaeformis Brady

Brady 1884, pl. 28, figs 2, 6.

Remarks: Branching tubes with relatively large diameter; wall of relatively coarse grains.

External tube diameter: 0.25 - 0.30 mm.

Depth range: 1419 - 2432 m, living; 1419 - 2432 m.

Occurrence: Common on mid and lower slope.

Rhizammina sp.

Remarks: Similar to R. algaeformis but tubes relatively narrow and wall composed of relatively fine grains; tubes repeatedly branching; tectinous lining collapses when dried to form flat ribbon.

External tube diameter: 0.10 - 0.15 mm.

Depth range: 1240 - 2469 m, living: 1240 - 2469 m.

Occurrence: Abundant on mid and lower slope, many specimens living.

Bathysiphon aff. argenteus Heron-Allen and Earland

Remarks: Pale orange-brown tubes, paler at extremities; wall moderately smooth; test straight or gently curved, occasionally twisted.

External tube diameter: 0.05 - 0.08 mm, rarely 0.10 mm.

Depth range: 1240 - 2432 m, living: 2432 m.

Occurrence: Rare, on mid and lower slope.

Bathysiphon globigeriniformis Hofker

Remarks: Pale orange-brown tube with many tests of foraminifera attached, attached foraminifera as much as 0.4 mm in length.

External diameter of orange-brown tube: about 0.10 mm.

Depth range: 19 - 2469 m, living: 1419 - 2469 m.

Occurrence: Occurs mainly on mid and lower slope, rare elsewhere.

Bathysiphon spp.

Remarks: Wall of coarse silt or very fine sand grains, most specimens have rough finish, some specimens tapered.

External tube diameter: 0.12 - 0.25 mm.

Depth range: 1419 - 2469m, living: 2028 - 2329 m.

Occurrence: Mid and lower slope only.

Marsipella elongata Norman

Brady 1884, pl. 24, figs 16, 17.

Remarks: Somewhat smaller than Brady's specimens.

Length: About 0.5 mm, maximum width about 0.12 mm.

Depth range: 2432 m, no living specimens.

Occurrence: Rare, on lower slope only.

Subfamily HIPPOCREPININAE

Hyperammina friabilis Brady

Remarks: Specimens vary greatly in size but are consistent in other characters, wall moderately rough.

Length: 1.1 - 7.5 mm, maximum external diameter: 0.3 - 1.7 mm.

Depth range: 1419 - 2432 m, no living specimens.

Occurrence: Rare, on mid and lower slope.

Jaculella acuta Brady

Brady 1884, pl. 22, figs 14 - 18.

Length: 2.0 - 3.0 mm, maximum external diameter: 0.6 - 0.8 mm.

Depth range: 2028 - 2063 m, no living specimens.

Occurrence: Rare, on lower slope only.

Family SACCAMMINIDAE

Subfamily PSAMMOSPHAERINAE

Psammosphaera fusca Schulze

Brady 1884, pl. 18, fig. 1.

Length: 0.2 - 0.4 mm.

Depth range: 40 - 2469 m, living: 40 - 2432 m.

Occurrence: A few specimens at most stations.

Psammosphaera parva Flint

Brady 1884, pl. 18, fig. 4.

Length (excluding spicule): About 0.4 mm.

Depth range: 1240 - 2028m, living: 2028 m.

Occurrence: Single specimens at two stations.

Storthosphaera albida Schulze

Brady 1884, pl. 25, fig. 15 - 17.

Remarks: Projections not so pronounced as in Brady's figures; some planktonic foraminifera incorporated in wall.

Length: About 0.4 mm.

Depth range: 1419 - 2063 m, living: 1419 m.

Occurrence: Rare, on mid and lower slope.

Subfamily SACCAMMININAE

Saccammina cushmani (Collins)

Remarks: Originally described as Proteonina; test tapering to small aperture.

Length: 0.1 - 0.3 mm.

Depth range: 329 - 2469 m, living: 329 - 2432 m.

Occurrence: Common at most places on the continental slope.

Saccammina sphaerica Sars

Brady 1884, pl. 18, fig. 15.

Remarks: Spherical with slightly protruding aperture.

Length: 0.3 - 1.0 mm.

Depth range: 329 - 2469 m, living: 329 - 1419 m.

Occurrence: A few specimens at most stations on slope.

Brachysiphon corbuliniformis Chapman

Lewis 1970, frontispiece.

Length: 0.5 - 1.0 mm.

Depth range: 2432 - 2469 m, no living specimens.

Occurrence: Rare, only at two deepest stations.

Lagenammina bulbosa (Chapman and Parr)

Remarks: Originally described as Proteonina; tiny with fine grained neck; large specimens of similar shape but with coarse grained neck are referred to Hormosina globulifera.

Length: About 0.15 mm.

Depth range: 2063 - 2469 m, living: 2063 - 2432 m.

Occurrence: Rare, on lower slope only.

Lagenammina difflugiformis (Brady)

Brady 1884, pl. 30, fig. 3; see also original figure.

Remarks: Some specimens more elongate than Brady's figure, and some have delicate phialine lip.

Length: 0.28 - 0.65 mm.

Depth range: 1240 - 2469 m, living: 1240 - 2469 m.

Occurrence: Common lower slope, less common on mid slope.

Lagenammina sp.

Remarks: Test small, delicate, fusiform, pale orange; wall fine grained; little variation.

Length: about 0.20 mm; width: about 0.09 mm.

Depth range: 1649 - 2469 m, living: 1649 m.

Occurrence: Rare, mid and lower slope.

Pelosina didera (Loeblich and Tappan)

Remarks: Originally described as Pelosinella.

External diameter of central chamber: 0.35 mm.

Depth range: 1649 - 2329 m, no living specimens.

Occurrence: Single specimens at two stations.

Pelosina aff. bicaudata (Parr)

Loeblich and Tappan 1964, fig. 112, no. 8.

Remarks: Mostly smaller than Loeblich and Tappan's figured specimen.

Length: 0.3 - 0.5 mm, maximum width: 0.09 - 0.16 mm.

Depth range: 1240 - 2469 m, living: 1240 - 2469 m.

Occurrence: Common at one station on lower slope.

Thurammina albicans Brady

Brady 1884, pl. 37, figs 2 - 7.

Length: About 0.20 mm.

Depth range: 186 - 2432 m, no living specimens.

Occurrence: Rare, mainly on mid and lower slope.

Thurammina castanea Heron-Allen and Earland

Heron-Allen and Earland 1917, pl. 26, fig. 15.

Length: Including tubes, About 0.10 mm.

Depth range: 1419 - 2469 m, living: 1419 m.

Occurrence: Rare, mid and lower slope.

Thurammina heusleri Heron-Allen and Earland

Heron-Allen and Earland 1917, pl. 28, figs 4, 6, 9.

Brady 1884, pl. 36, fig. 14.

Length: 0.15 - 0.20 mm.

Depth range: 2469 m.

Occurrence: Rare, at deepest station only.

Family AMMODISCIDAE

Subfamily AMMODISCINAE

Ammodiscus gullmarensis Höglund

Remarks: Surface not polished ; coiling tending to become irregular.

Length: 0.18 - 0.22 mm.

Depth range: 48 - 2329 m, living: 48 - 1240 m.

Occurrence: Rare, most frequent on mid and lower slope.

<u>Ammodiscus planorbis</u> Höglund

Remarks: Wall brown and highly polished.

Length: 0.3 - 0.5 mm.

Depth range: 186 - 2329 m, living: 276 - 1240 m.

Occurrence: A few specimens at many stations on slope.

<u>Ammodiscus tenuis</u> Brady

Lewis 1970, frontispiece.

Length: 0.7 - 1.6 mm.

Depth range: 276 - 479 m, living: 375 m.

Occurrence: Rare, on upper slope only.

<u>Glomospira charoides</u> (Jones and Parker)

Brady 1884, pl. 38, figs 13, 14.

Length: About 0.25 mm.

Depth range: 1419 - 2329 m, no living specimens.

Occurrence: Most common on mid slope.

<u>Glomospira</u> cf. <u>elongata</u> Collins

Remarks: Smaller than Collin's original figures.

Length: About 0.15 mm.

Depth range: 1419 m, no living specimens.

Occurrence: Rare, at single station on mid slope.

Glomospira gordialis (Jones and Parker)

Loeblich and Tappan 1964, fig. 122, no. 6.

Remarks: Many specimens even more irregular than Loeblich and Tappan's figure.

Length: 0.15 - 0.25 mm, diameter of tube: 0.04 - 0.06 mm.

Depth range: 186 - 2469 m, living: 375 - 2329 m.

Occurrence: A few specimens at most station on slope, most common on mid slope.

Subfamily TOLYPAMMININAE

Tolypammina vagans (Brady)

Brady 1884, pl. 24, figs 1 - 5.

Remarks: Cemented to other foraminifera.

External diameter of tube: About 0.08 mm.

Depth range: 2432 - 2469 m, living: 2432 m.

Occurrence: Rare.

Superfamily LITUOLACEA

Family HORMOSINIDAE

Subfamily ASCHEMONELLINAE

Aschemonella catenata (Norman)

Brady 1884, pl. 27, fig. 3.

Remarks: The specimens fit Loeblich and Tappan's (1964) description that A. catenata is a smaller and more delicate form than A. scabra with chambers tending to be bulbous rather than elongate; tectinous lining tends to collapse when dried.

External diameter of each chamber: About 0.5 mm.

Depth range: 2469 m, no living specimens.

Occurrence: Rare, at deepest station.

Aschemonella scabra Brady

Brady 1884, pl. 27, figs 1, 5.

External diameter of each chamber: About 1.0 mm.

Depth range: 2439 - 2469 m, no living specimens.

Occurrence: Rare, at two deepest stations.

Subfamily HORMOSININAE

Hormosina globulifera Brady

Brady 1884, pl. 39, figs 1 - 4; Lewis 1970, frontispiece.

Length: 0.4 - 1.5 mm.

Depth range: 329 - 2469 m, living: 329 - 2063 m.

Occurrence: Moderately common at most stations on continental slope.

Reophax bacillaris Brady

Brady 1884, pl. 30, figs 23, 24.

Length: 1.0 - 1.5 mm, width of final chamber:

0.20 - 0.30 mm.

Depth range: 625 m, no living specimens.

Occurrence: Rare, at single station.

Reophax dentaliniformis Brady

Brady 1884, pl. 30, figs 21, 22.

Remarks: Smaller than Brady's figures and 2 - 4 chambers.

Length: 0.6 - 1.4 mm, width of final chamber: 0.15 - 0.30 mm.

Depth range: 479 - 2469 m, living: 479 - 2469 m.

Occurrence: Moderately common at most stations on mid and lower slope.

Reophax distans Brady

Brady 1884, pl. 31, figs 18, 19.

External diameter of each chamber: About 0.5 mm.

Depth range: 2028 - 2432 m, no living specimens.

Occurrence: Rare, on lower slope.

Reophax guttifer Brady

Brady 1884, pl. 31, figs 10 - 15.

Remarks: Some specimens have a few spicules projecting, these give the test a hispid appearance.

External diameter of chambers: 0.16 - 0.22 mm.

Depth range: 304 - 2469 m, living: 1439 m.

Occurrence: Rare on upper and mid slope, more common on lower slope.

Reophax aff. guttifer Brady

Remarks: Smaller and more delicate than R. guttifer; wall fine grained and almost smooth, 2 - 4 chambers.

External diameter of chambers: 0.11 - 0.14 mm.

Depth range: 1240 - 2432 m, living: 1240 - 2432 m.

Occurrence: Moderately common on mid slope.

Reophax micaceus Earland

Remarks: Test wall includes grains other than mica but shape and size as R. micaceus; test of 1 - 5 chambers.

Length: 0.4 - 0.9 mm, diameter of chamber: 0.14 - 0.16 mm.

Depth range: 2469 m, no living specimens.

Occurrence: Rare.

Reophax scorpiurus Montfort

Hedley et al 1965, pl. 1, fig. 1.

Length: 0.8 - 1.2 mm.

Depth range: 71 - 2028 m, living: 71 - 479 m.

Occurrence: Almost ubiquitous but rare at any station.

Reophax subfusiformis Earland

Höglund 1947, pl. 9, figs 1, 2, 4.

Remarks: Coarse grained wall, neck fine with phialine lip.

Length: About 0.9 mm.

Depth range: 329 m.

Occurrence: Rare, on Motukura Bank only.

Reophax spp.

Remarks: Specimens of several small thin-walled species of Reophax.

Length: 0.3 - 0.9 mm.

Occurrence: Mainly on mid slope.

Family LITUOLIDAE

Subfamily HAPLOPHRAGMOIDINAE

Haplophragmoides canariensis (d'Orbigny)

Remarks: Small, thin-walled, smooth, moderately compressed.

Length: 0.25 - 0.35 mm.

Depth range: 18 - 2432 m, living: 18 - 2432 m.

Occurrence: Moderately common on shelf, rare on slope.

Haplophragmoides cf. scitulum (Brady)

cf. Brady 1884, pl. 34, figs 11 - 13.

Remarks: Test tiny, well rounded with wide apertural face and deep umbilicus, with 5-6 chambers in whorl; wall pale orange and polished.

Length: 0.11 - 0.14 mm.

Depth range: 375 - 1439m, living: 375 - 1439 m.

Occurrence: Rare, on upper and mid slope.

Haplophragmoides sphaeriloculus Cushman

Remarks: Specimens from study area smaller than holotype.

Length: 0.30 - 0.45 mm.

Depth range: 186 - 2469 m, no living specimens.

Occurrence: Rare and at few stations.

Haplophragmoides subtrullissatus Parr

Remarks: Chambers in whorl range from 5 - 7, larger specimens having relatively more. Wall of fairly large grains neatly fitted together to form smooth surface.

Length: 0.5 - 1.0 mm.

Depth range: 91 - 1439 m, living: 91 - 1439 m.

Occurrence: Moderately common on outer shelf and upper slope.

Haplophragmoides trullissata (Brady)

Brady 1884, pl. 40, fig. 13.

Remarks: Wall is not labyrinthic but shows merely "a few slightly raised reticulations" (Brady 1879); finer-grained, more polished, and darker orange-brown in colour than *H. subtrullissata*; periphery relatively angular.

Length: 0.5 - 0.9 mm.

Depth range: 2432 m, no living specimens.

Occurrence: Rare, at single station.

Adercotryma glomeratum (Brady)

Brady 1884, pl. 34, figs 15 - 18.

Length (along axis): About 0.15 mm.

Depth range: 1240 - 2469 m, living: 1240 - 2469 m.

Occurrence: Common mid slope, fairly common on lower slope.

Cribrostomoides wiesneri Parr

Remarks: Usually 6 - 7 chambers in final whorl.

Length: 0.30 - 0.45 mm.

Depth range: 48 - 2432 m, living: 48 - 2329 m.

Occurrence: Ubiquitous, common at a few stations on mid and lower slope.

Cribrostomoides sp.

Wiesner 1931, pl. 11, fig. 135.

Remarks: Test, small, white or pale orange; 5 - 6 globose chambers in final whorl; wall of coarse grains but moderately smooth finish; aperture at base of terminal face with recessed lower lip.

Length: 0.3 - 0.5 mm.

Depth range: 40 - 375 m, living: 71 - 375 m.

Occurrence: Common on outer shelf, less common on inner shelf and upper slope.

Discammina compressa (Goes)

Loeblich and Tappan 1964, fig. 136, no. 10.

Remarks: Specimens are so coarse grained that it is difficult to see sutures.

Length: 0.4 - 0.6 mm.

Depth range: 2432 m, no living specimens.

Occurrence: Rare.

Recurvoides contortus Earland

Remarks: Wall of moderately coarse grains but neatly fitted together and surface smooth or polished.

Length: 0.4 - 0.7 mm.

Depth range: 276 - 2469 m, living: 276 - 2469 m.

Occurrence: Common at some stations on mid and lower slope.

Recurvoides sp.

Remarks: Test larger and more globose than R. contortus, apertural face broader with more slit-like aperture; wall of large grains but smoothly finished. Possibly the same as R. turbinatus of Loeblich and Tappan 1953, pl. 2, fig. 11.

Length: 0.5 - 0.8 mm.

Depth range: 1240 - 2432 m, no living specimens.

Occurrence: Rare.

Subfamily CYCLAMMININAE

Cyclammina cancellata Brady

Brady 1884, pl. 37, figs 8 - 16.

Remarks: Many specimens with chambers more globose than is shown in Brady's figures.

Length: 1.0 - 1.5 mm.

Depth range: 479 - 1649 m.

Occurrence: Rare.

Cyclammina aff. pusilla Brady

Wiesner 1931, pl. 8, fig. 151.

Length: 0.6 - 0.7 mm.

Depth range: 304 m, no living specimens.

Occurrence: Rare.

Alveolophagmium zealandicum Vella

Length: 0.55 - 0.80 mm.

Depth range: 142 - 2469 m, living: 2432 m.

Occurrence: Rare, on banks and slope.

Subfamily LITUOLINAE

Ammobaculites filiformis Earland

Earland 1934, pl. 3, figs 11, 13; Brady 1884, pl. 32, fig. 22.

Remarks: Small, with rough surface and moderately globose chambers; growth tends to be irregular.

Length: 0.4 - 0.7 mm, width: 0.07 mm.

Depth range: 1240 - 2432 m, living: 1240 m.

Occurrence: Moderately common on mid slope.

Ammobaculites aff. filiformis Earland

Earland 1934, pl. 3, fig. 12; Brady 1884, pl. 32, fig. 23.

Remarks: Relatively smooth walled, chambers not globose and sutures not as deep as A. filiformis; growth regular. Appears to be quite distinct from A. filiformis.

Length: 0.4 - 0.7 mm, width: 0.07 - 0.09 mm.

Depth range: 1240 - 2432 m, living: 1240 - 2432 m.

Occurrence: Common on mid and lower slope, occurs at almost every station.

Ammomarginulina cf. ensis Wiesner

Remarks: Initial coil same size and shape as A. ensis but only 1 - 3 uncoiled chambers; colour pale orange-brown.

Length: 0.20 - 0.35 mm.

Depth range: 329 - 2329 m, living: 329 - 2329 m.

Occurrence: Common at some stations on continental slope.

Ammomarginulina cf. foliaceus (Brady)

cf. Brady 1884, pl. 33, figs 20 - 25.

Remarks: Similar to Brady's figure but with thin, fragile keel of fine grains; rest of test coarse grained; central area orange-brown, keel white.

Length: 0.5 - 1.2 mm, width: 0.15 - 0.25 mm.

Depth range: 304 - 2432 m, living: 304 - 1419 m.

Occurrence: Moderately common at some stations on upper and mid slope.

Ammoscalaria tenuimargo (Brady)

Höglund 1947, pl. 31, fig. 2.

Remarks: Considerable variation in size of initial coil.

Length: 0.9 - 1.6 mm.

Depth range: 1240 - 2432 m, living: 1240 - 2432 m.

Occurrence: Rare.

Family TEXTULARIIDAE

Subfamily SPIROPLECTAMMININAE

Spiroplectammina cf. biformis Parker and Jones

Brady 1884, pl. 45, fig. 25.

Remarks: Some specimens are longer than Brady's figure with one or two uniserial chambers.

Length: 0.20 - 0.40 mm, width: about 0.08 mm.

Depth range: 1240 - 2469 m, living: 1240 - 1419 m.

Occurrence: Common on mid slope, moderately common on lower slope.

Subfamily TEXTULARIINAE

Textularia conica d'Orbigny

Brady 1884, pl. 43, figs 13, 14.

Length: 0.4 - 1.0 mm.

Depth range: 40 - 427 m, living: 42 - 427 m.

Occurrence: Common on inner shelf and Madden Banks, i.e. where sediment is relatively coarse.

Textularia earlandi Parker

Höglund 1947, pl. 13, fig. 1, text-fig. 154 - 155.

Length: 0.3 - 0.5 mm.

Depth range: 40 - 1419m, living: 71 - 1240 m.

Occurrence: Common on outer shelf.

Textularia proxispira Vella

Remarks: Specimens show large variation in size.

Length: 0.30 - 0.75 mm.

Depth range: 18 - 427 m, no living specimens.

Occurrence: Rare.

Textularia aff. sagittula Defrance

Brady 1884, pl. 42, fig. 18.

Remarks: Compressed with angular periphery; fine grained with glassy nodes in central portion; periphery white, rest orange-brown; some specimens have conspicuous initial coil.

Length: 0.5 - 1.1 mm.

Depth range: 183 - 1649 m, no living specimens.

Occurrence: Rare.

Subfamily PSEUDOBOLIVININAE

Pseudobolivina sp.

Heron-Allen and Earland 1922, pl. 4, figs 31 - 35.

Remarks: Tiny, fragile, pale orange-brown, twisted growth.

Length: About 0.20 mm.

Depth range: 130 - 186 m, no living specimens.

Occurrence: Rare.

Siphotextularia fretensis Vella

Length: 0.35 - 0.65 mm.

Depth range: 186 - 1240 m, living: 186 - 375 m.

Occurrence: Abundant on banks, common on upper slope.

Siphotextularia aff. fretensis Vella

Remarks: Smaller and more narrow than S. fretensis with deeper sutures, thinner, more finely grained wall and aperture on conspicuous protruding neck.

Length: 0.2 - 0.4 mm.

Depth range: 2329 - 2432 m, no living specimens.

Occurrence: Rare.

Siphotextularia mestayerae Vella

Length: About 0.75 mm.

Depth range: 142 - 625 m, no living specimens.

Occurrence: Common on North Madden Bank.

Family TROCHAMMINIDAE

Subfamily TROCHAMMININAE

Trochammina ? aff. globigeriniformis (Parker and Jones)

Remarks: Test tiny, smooth-walled, orange-coloured, with a total of 5 - 6 globose chambers, 3 - 4 of them in final whorl. Too few chambers to be sure that coiling is trochospiral, it may be streptospiral.

Length: 0.09 - 0.13 mm.

Depth range: 1419 - 2329 m, living: 1439 - 2028 m.

Occurrence: Moderately common on mid slope.

Trochammina inflata (Montague)

Hedley et al 1967, pl. 6, fig. 3; Brady 1885, pl. 41, fig. 4.

Remarks: Wall fine grained and smooth; 5 - 5½ chambers in final whorl; sutures clear but not as depressed as those of T. rotaliformis.

Length: 0.18 - 0.35 mm.

Depth range: 329 - 2432 m, living: 329 - 1619 m.

Occurrence: A few specimens at most stations on continental slope.

Trochammina ochracea (Williamson)

Hedley et al 1964, fig. 2, no. 2.

Remarks: Considerable variation in shape and height of sutural ridges on umbilical side.

Length: 0.15 - 0.25 mm.

Depth range: 71 - 427 m, living: 91 - 427 m.

Occurrence: Moderately common on outer shelf.

Trochammina pusilla Höglund

Remarks: Tiny, coarse grained, fragile, 3 - 4 globose chambers in final whorl, very pale orange, considerable variation in height of spire.

Length: 0.15 - 0.30 mm.

Depth range: 71 - 2432 m, living: 71 - 2432 m.

Occurrence: Occurs at almost every station from outer shelf to lower slope, common on mid and lower slope.

Trochammina sorosa Parr

Hedley et al 1967, text-fig. 11 - 15.

Remarks: Test small orange fairly smooth with 4 chambers in final whorl.

Length: 0.20 - 0.30 mm.

Depth range: 42 - 2469 m, living: 48 - 427 m.

Occurrence: Moderately common at a few isolated stations.

Trochammina squamata Jones and Parker

Hedley et al 1964, fig. 1, no. 1.

Remarks: Most specimens smaller and more regular than the figures of Hedley et al; low spires with 4 chambers in final whorl; wall smooth.

Length: 0.12 - 0.22 mm.

Depth range: 18 - 1240 m, living: 18 - 1240 m.

Occurrence: Moderately common on shelf, rare on slope.

Trochammina sp.

Remarks: Test small with flat spiral side and high domed umbilical side; periphery angular; about 3 whorls on spiral side and about 7 chambers in final whorl; wall relatively coarse for test size but smoothly finished. Much smaller and more finely grained than T. planoconvexa.

Length: 0.10 - 0.15 mm.

Depth range: 48 - 113 m, living: 48 - 113 m.

Occurrence: Moderately common on outer shelf.

Ammosphaeroidina sphaeroidiniformis (Brady)

Loeblich and Tappan 1964, fig. 174, no. 1.

Remarks: Considerable variation in size and wall texture.

Length: 0.30 - 0.75 mm.

Depth range: 329 - 2432 m, living: 479 - 2329 m.

Occurrence: A few specimens at most stations on continental slope, common only on mid slope.

Cystammina pauciloculata (Brady)

Brady 1884, pl. 41, fig. 1.

Length: 0.25 - 0.45 mm.

Depth range: 1419 - 2469 m, living: 2329 - 2469 m.

Occurrence: Moderately common on lower slope.

Tritaxis conica (Parker and Jones)

Brady 1884, pl. 49, fig. 16.

Length: (height of cone) 0.15 mm.

Depth range: 40 - 1419 m, no living specimens.

Occurrence: Single specimens attached to sand grains at two stations.

Family ATAXOPHRAGMIIDAE

Subfamily VERNEUILININAE

Gaudryina convexa (Karrer)

Burdett et al 1963, figs 2 - 6.

Length: 0.7 - 1.2 mm.

Depth range: 42 - 183 m, no living specimens.

Occurrence: Only at stations where sediment is sand or calcarenite.

Subfamily GLOBOTEXTULARIINAE

Eggerella bradyi (Cushman)

Brady 1884, pl. 47, figs 4 - 6.

Remarks: Specimens white and mainly calcareous, aperture with raised lip.

Length: 0.4 - 1.1 mm.

Depth range: 625 - 2469 m, living: 625 - 1419 m.

Occurrence: Common on mid slope, moderately common on lower slope.

Eggerella scabra (Williamson)

Brady 1884, pl. 47, figs 15 - 17.

Remarks: Smaller specimens are more fine grained and have a smoother wall than large specimens.

Length: 0.16 - 0.35 mm.

Depth range: 18 - 2432 m, living: 1419 - 1649 m.

Occurrence: A few specimens at many stations, moderately common on mid slope.

Karreriella apicularis (Cushman)

Brady 1884, pl. 46, fig. 17.

Remarks: Wall coarse grained, rough, and orange-brown.

Length: 0.35 - 0.85 mm.

Depth range: 1240 - 2469 m, living: 1240 - 2329 m.

Occurrence: Moderately common on mid and lower slope.

Karreriella bradyi (Cushman)

Brady 1884, pl. 46, figs 1 - 4, also figs 9, 10.

Remarks: Most specimens resemble Brady's figures

1 - 4 but some aberrant specimens resemble figures 9, 10 which Brady and subsequent authors have regarded as a separate species. Aperture slit with raised lip.

Length: 0.60 - 0.95 mm.

Depth range: 625 - 2127 m, living: 1419 m.

Occurrence: Common at a few stations.

Subfamily VALVULININAE

Martinottiella cf. communis (d'Orbigny)

cf. Brady 1884, pl. 48, figs 1 - 8.

Remarks: Test smaller than Brady's figures and wall composed of even sized grains; apertural face flattened with aperture at end of distinct neck.

Length: 1.0 - 1.9 mm, width: 0.40 - 0.45 mm.

Depth range: 276 - 625 m, no living specimens.

Occurrence: Rare, at only two stations.

Suborder MILIOLINA

Superfamily MILIOLACEA

Family FISCHERINIDAE

Subfamily CYCLOGRYINAE

Cornuspiroides foliaceus (Philippi)

Brady 1884, pl. 11, fig. 6.

Length: About 0.4 mm.

Depth range: 276 - 2063 m, living: 625 m.

Occurrence: Rare.

Family NUBECULARIIDAE

Subfamily SPIROLOCULININAE

Spiroloculina acutimargo (Brady)

Brady 1884, pl. 10, figs 12, 13.

Remarks: Brady's figure 12 is the type figure of S. acutimargo and cannot, therefore, be referred to S. elevata (Wiesner, quoted in Barker 1960). Specimens illustrated by Vella (1957) pl. 6, figs 122, 123 are considered to be S. acutimargo not S. disparilis which is a more elongate form from the Pliocene of Greece.

Length: 0.55 - 0.95 mm.

Depth range: 18 - 1419 m, no living specimens.

Occurrence: Rare, at only a few stations.

Family MILIOLIDAE

Subfamily QUINQUELOCULININAE

Quinqueloculina colleenae Vella

Remarks: Chambers quadrate with frilled, carinate periphery; possibly a variant of Q. cooki.

Length: 0.75 - 1.10 mm.

Depth range: 142 - 183 m.

Occurrence: Only on Madden Banks where common.

Quinqueloculina cooki Vella

Remarks: Chambers quadrate but not carinate.

Length: 0.35 - 0.95 mm.

Depth range: 40 - 48 m, no living specimens.

Occurrence: Rare.

Quinqueloculina incisa Vella

Remarks: Distinguished by having perfectly rounded chambers.

Length: 0.30 - 0.75 mm.

Depth range: 18 - 2329 m, living: 18 - 48 m.

Occurrence: Moderately common on inner shelf, single specimen from lower slope.

Quinqueloculina kapitiensis Vella

Remarks: No specimens have brownish-yellow bands referred to in the original description and some have their aperture on a slight neck.

Length: 0.35 - 0.50 mm.

Depth range: 18 - 113 mm, living: 18 - 113 m.

Occurrence: Moderately common on inner and outer shelf.

Quinqueloculina lamarkiana d'Orbigny

Vella 1957, pl. 6, figs 105 - 107.

Remarks: Similar to Q. triangularis but with an angular periphery that is curved towards the direction of growth.

Length: 0.40 - 0.80 mm.

Depth range: 18 - 91 m, living: 91 m.

Occurrence: Moderately common on shelf.

Quinqueloculina aff. lata Terquem

Vella 1957, pl. 6, figs 112 - 114.

Remarks: More elongate than Q. triangularis with distinct L-shaped chambers.

Length: 0.25 - 0.40 mm.

Depth range: 18 - 48 m, living: 18 - 48 m.

Occurrence: Common at some stations on inner shelf.

Quinqueloculina neosigmoilinoides Kennett

Vella 1957, pl. 6, figs 116, 117.

Remarks: Included are all specimens with subangular periphery that appear sigmoidal in apertual view. Shape in side view varies from elongate specimens similar to holotype to specimens that are almost circular in side view.

Length: 0.35 - 0.60 mm.

Depth range: 18 - 1439 m, living: 18 - 427 m.

Occurrence: Common shelf, rare on slope.

Quinqueloculina suborbicularis d'Orbigny

Vella 1957, pl. 6, figs 105 - 107.

Remarks: More nearly circular in side view than Q. triangularis but otherwise smaller.

Length: 0.20 - 0.50 mm.

Depth range: 18 - 48 m, no living specimens.

Occurrence: Rare, on inner shelf.

Quinqueloculina triangularis d'Orbigny

Vella 1957, pl. 6, figs 100, 101, 108; Hedley et al 1965, pl. 2, fig. 8.

Remarks: Specimens of this species have frequently been recorded as Q. seminulum which is distinctly more elongate (cf. Loeblich and Tappan 1964, fig. 349, no. 1) than Q. triangularis.

Length: 0.5 - 1.2 mm.

Depth range: 18 - 329 m, living: 42 - 329 m.

Occurrence: Moderately common on inner shelf and on banks.

Quinqueloculina cf. venusta Karrer

Remarks: Small, triangular with slightly raised edges in apertural view, aperture rounded with tooth and sometimes on slight neck, no lip.

Length: 0.23 - 0.40 mm.

Depth range: 1649 - 2432 m, no living specimens.

Occurrence: Common at two stations on mid and lower slope.

Quinqueloculina wiesneri Parr

Remarks: Described by Parr (1950) as Q. anguina var.; small with aperture on neck and phialine lip.

Length: 0.25 - 0.30 mm.

Depth range: 375 - 2432 m, living: 2432 m.

Occurrence: Common only on lower slope.

Massilina brodiei Hedley, Hurdle and Burdett

Length: 0.35 - 0.45 mm.

Depth range: 18 - 40 m.

Occurrence: Rare.

Pyrgo murrhyna (Schwager)

Brady 1884, pl. 2, figs 10, 11, 15.

Remarks: Periphery with two points near base, periphery of some specimens is serrated; aperture rounded with bifid tooth.

Length: 0.9 - 1.6 mm.

Depth range: 372 - 2432 m, living: 2063 m.

Occurrence: Rare, at only a few stations.

Pyrgo pisum (Schlumberger)

Vella 1957, pl. 7, figs 130, 135, 136, 138, 139, 144, 145.

Remarks: Large population from the North Madden Bank shows that this is a very variable species. There appears to be continuous variation between forms recorded by Vella (1957) as Biloculina pisum, B. anomala, B. guerreri and Pyrgo aff. ezo.

Length: 0.75 - 1.35 mm.

Depth range: 142 - 1649 m, living: 329 - 375 m.

Occurrence: Common North Madden Bank, rare elsewhere.

Pyrgoella sphaera (d'Orbigny)

Brady 1884, pl. 2, fig. 4.

Length: 0.30 - 0.55 mm.

Depth range: 276 - 625 m, no living specimens.

Occurrence: Rare.

Sigmoilopsis schlumbergeri (Silvestri)

Brady 1884, pl. 8, figs 1 - 4.

Length: 0.25 - 0.55 mm.

Depth range: 1240 - 2469 m, living: 1419 m.

Occurrence: Common on mid slope, rare on lower slope.

Sigmoilopsis wanganuienesis Vella

Length: About 0.7 mm.

Depth range: 329 - 2028 m, no living specimens.

Occurrence: Abundant on bank, rare elsewhere.

Siphonaperta crassa Vella.

Remarks: A few specimens have a fragile neck with phialine lip preserved.

Length: 0.7 - 1.1 mm.

Depth range: 186 - 329 m, no living specimens.

Occurrence: Common only on Madden Banks.

Siphonaperta macbeathi Vella

Remarks: Smaller than most fossil specimens.

Length: 0.3 - 0.4 mm.

Depth range: 40 - 329 m, living: 40 m.

Occurrence: Occurs where sediments coarse on inner shelf and on banks.

Siphonaperta parvaggluta (Vella)

Length: 0.20 - 0.35 mm.

Depth range: 42 - 48 m, no living specimens.

Occurrence: Rare.

Triloculina trigonula (Lamarck)

Brady 1884, pl. 3, figs 15, 16.

Length: 0.47 - 0.67 mm.

Depth range: 142 - 183 m, no living specimens.

Occurrence: On Madden Banks only.

Subfamily MILIOLINELLINAE

Miliolinella subrotunda (Montague)

Brady 1884, pl. 4, fig. 3; pl. 5, figs 10, 11, 13, 14.

Loeblich and Tappan 1964, fig. 335, no. 1.

Remarks: Large specimens are typical of M. subrotunda but small specimens which tend to be flattened with chambers in planospiral or streptospiral coil, are similar to M. australis (Parr).

Length: 0.25 - 0.55 mm.

Depth range: 18 - 183 m, living: 42 - 48 m.

Occurrence: Moderately common on inner shelf and on Madden Banks; may occur only where sediment is relatively coarse.

Biloculinella depressa (d'Orbigny)

Vella 1957, pl. 7, fig. 137, 140.

Length: 0.75 - 1.00 mm.

Depth range: 42 - 375 m, living 42 m.

Occurrence: Inner shelf and Madden Banks where sediment relatively coarse.

Scutuloris hornibrooki (Vella)

Length: About 0.3 mm.

Depth range: 48 - 2028 m, living: 48 - 2028 m.

Occurrence : Rare, occurs at only two stations.

Suborder ROTALIINA

Superfamily NODOSARIACEA

Family NODOSARIIDAE

Subfamily NODOSARIIDAE

Nodosaris calomorpha Reuss

Brady 1884, pl. 61, figs 23 - 27.

Length: About 0.3 mm.

Depth range: 329 - 2127 m, no living specimens.

Occurrence: A few specimens at many stations on slope.

Nodosaria simplex (Silvestri)

Brady 1884, pl. 62, fig. 4.

Length: 0.6 - 0.7 mm.

Depth range: 276 m, no living specimens.

Occurrence: Rare.

Amphicoryna hirsuta (d'Orbigny)

Brady 1884, pl. 63, figs 12 - 15.

Length: 0.50 - 0.75 mm.

Depth range: 276 - 625 m, no living specimens.

Occurrence: Common on bank, rare elsewhere.

Amphicoryna separans (Brady)

Brady 1884, pl. 63, figs 29 - 31; pl. 64, figs 16 - 19; pl. 65, figs 7 - 9.

Remarks: All of Brady's figured specimens are from the Pacific, most are from New Zealand. Those recorded as A. scalaris by Barker (1960) are immature specimens of A. separans. A. scalaris (Brady 1884, pl. 63, fig. 28) has no ribs around neck and is probably confined to the Atlantic Ocean.

Length: 0.7 - 1.8 mm.

Depth range: 71 - 625 m, no living specimens.

Occurrence: Rare.

Astacolus sp.

Remarks: Angular periphery and broad, globose apertural face; tends towards shape of Saracenaria; resembles Lenticulina altifrons (Parr) but less tightly enrolled initial coil.

Length: 0.6 - 0.9 mm.

Depth range: 276 - 375 m, living: 329 m.

Occurrence: Common on bank, rare on upper slope.

Dentalina cf. caudata d'Orbigny

Length: 0.45 - 0.90 mm.

Depth range: 276 - 329 m, no living specimens.

Occurrence: Rare.

Dentalina spp. aff. filiformis (d'Orbigny)

Brady 1884, pl. 63, figs 3 - 5.

Length: 0.5 - 2.0 mm.

Depth range: 18 - 1240 m, living: 304 - 375 m.

Occurrence: A few specimens at many stations.

Dentalina subemaciata Parr

Length: 0.8 - 2.5 mm.

Depth range: 276 - 2432 m, living: 304 - 1419 m.

Occurrence: Common on bank and at some places on upper and mid slope.

Dentalina subsoluta (Cushman)

Brady 1884, pl. 62, figs 13 - 16.

Length: 1.0 - 4.3 mm.

Depth range: 113 - 625 m, no living specimens.

Lagena spp.

Remarks: It was found difficult to group specimens of Lagena into well defined species so they were counted collectively and the presence of some conspicuous forms was noted. These forms are listed below.

Lagena elongata (Ehrenberg)

Brady 1884, pl. 56, figs 27, 29.

Occurrence: Rare, occurs at several stations on slope.

Lagena gracilis Williamson

Brady 1884, pl. 58, figs 1, 2, 23.

Occurrence: Fairly common on outer shelf and slope.

Lagena gracillima (Seguenza)

Brady 1884, pl. 56, figs 21, 22.

Occurrence: Rare, inner shelf only.

Lagena hispida Reuss

Brady 1884, pl. 57, figs 2 - 4.

Occurrence: Rare, on upper slope and bank.

Lagena laevis

Brady 1884, pl. 56, figs 7, 8.

Occurrence: Fairly common on banks and slope.

Lagena aff. laevis (Montague)

Brady 1884, pl. 57, fig. 14.

Occurrence: Rare, on outer shelf and slope.

Lagena plumigera Brady

Brady 1884, pl. 58, figs 18, 25, 27.

Occurrence: Rare, outer shelf and upper slope.

Lagena striata (d'Orbigny)

Brady 1884, pl. 57, figs 22, 24, 28.

Occurrence: Common from inner shelf to mid slope.

Lagena sulcata (Walker and Jacobs)

Brady 1884, pl. 58, figs 4, 17.

Occurrence: Rare, on bank and slope.

Lenticulina spp.

Remarks: Many species of Lenticulina are very variable and it was found difficult to assign many specimens to particular species. Therefore, all specimens of Lenticulina were counted collectively and the presence of some conspicuous species was noted. These species are listed below.

Occurrence: Common outer shelf and upper slope, abundant on banks.

Lenticulina calcar (Linnaeus)

Brady 1884, pl. 70, figs 11, 12.

Remarks: Glassy spines around periphery.

Occurrence: Rare, upper slope only.

Lenticulina cultratus (Montfort)

Hedley *et al* 1965, pl. 4, fig. 15.

Remarks: Sharp keel, and umbilical plug.

Occurrence: Occurs at most stations from inner shelf to lower slope, common on banks.

Lenticulina gibba (d'Orbigny)

Hedley *et al* 1965, pl. 3, fig. 11.

Remarks: No keel, no umbilical plug or very small umbilical plug.

Occurrence: Rare, on outer shelf and upper slope.

Lenticulina loculosa (Stache)

Hornibrook 1961, pl. 4, fig. 63.

Remarks: Many chambers in whorl, large umbilical plug, keel.

Occurrence: Rare, outer shelf to mid slope.

Lenticulina peregrina (Schwager)

Brady 1884, pl. 68, figs 11 - 16.

Remarks: One of the few really distinctive species.

Occurrence: Common and living on upper slope, common on bank, single specimens on outer shelf and on mid slope.

Lenticulina subgibba Parr

Hedley et al 1965, pl. 3, fig. 12.

Remarks: No keel, flaring.

Occurrence: Rare, outer shelf and upper slope.

Lenticulina suborbicularis (Parr)

Hedley et al 1965, pl. 5, fig. 16.

Remarks: Spiral sutures, small.

Occurrence: Rare, on bank and on inner shelf.

Lenticulina tasmanica (Parr)

Hedley *et al* 1965, pl. 5, fig. 17.

Remarks: Few chambers, large glassy umbilical plug, keel.

Occurrence: Rare, occurs on inner shelf and on mid slope.

Marginulina glabra d'Orbigny

Loeblich and Tappan 1964, fig. 406, no. 10.

Length: 0.8 - 1.1 mm, width: 0.40 - 0.55 mm.

Depth range: 329 - 2127 m, no living specimens.

Occurrence: Rare, at only two stations.

Marginulina tenuis Bornemann

Brady 1884, pl. 66, fig. 21.

Length: 1.1 - 1.6 mm, width: 0.19 - 0.24 mm.

Depth range: 276 - 329 m, no living specimens.

Occurrence: Common on bank, rare on upper slope.

? Marginulinopsis bradyi (Goes)

Brady 1884, pl. 65, fig. 12.

Remarks: Specimens appear to be referable to *Marginulina* but may be within the range of variation of *Marginulinopsis bradyi*.

Length: 1.6 - 3.2 mm, width: 0.50 - 0.55 mm.

Depth range: 142 - 329 m, no living specimens.

Occurrence: Rare, on banks.

Orthomorphina georgiana (Cushman)

Remarks: Described as Nodogenerina.

Length: About 0.6 mm.

Depth range: 18 - 429 m, no living specimens.

Occurrence: Rare.

Planularia tricarinella (Reuss)

Hedley et al 1965, pl. 4, fig. 13.

Length: 0.5 - 1.1 mm.

Depth range: 113 - 304 m, living: 113 - 276 m.

Occurrence: Rare.

Saracenaria latifrons (Brady)

Brady 1884, pl. 113, fig. 11.

Remarks: Sharp angles at each of three corners.

Depth range: 186 - 427 m, living: 427 m.

Occurrence: Common on bank, rare on upper slope.

Family POLYMORPHINIDAE

Subfamily POLYMORPHININAE

Sigmomorphina lacrimosa Vella

Length: 1.2 - 1.8 mm.

Depth range: 142 - 183 m, no living specimens.

Occurrence: Only on Madden Banks.

Subfamily RAMULININAE

Ramulina globulifera Brady

Brady 1884, pl. 76, figs 22 - 28.

Length of individual chambers: 0.3 - 0.5 mm.

Depth range: 329 - 479 m, no living specimens.

Occurrence: Common on bank, rare on upper slope.

Family GLANDULINIDAE

Subfamily GLANDULININAE

Entolingulina sp.

Remarks: Three chambers in rectilinear series.

Length: 1.65 mm.

Depth range: 2469 m, living: 2469 m.

Occurrence: Only at deepest station.

Laryngosigma hyalascidia Loeblich and Tappan

Loeblich and Tappan 1964, fig. 421, no. 9.

Length: 0.45 mm.

Depth range: 42 m, no living specimens.

Occurrence: Rare, at single station.

Subfamily SEABROOKIINAE

Seabrookia earlandi Wright

Remarks: Final chamber not completely enclosing earlier chambers.

Length: 0.16 - 0.25 mm.

Depth range: 186 - 2432 m, living: 329 - 1419 m.

Occurrence: Common at many stations on slope.

Seabrookia sp.

Remarks: Chambers even less embracing than S. earlandi; reminiscent of Edentostomina but wall clear and glassy.

Length: 0.16 - 0.20 mm.

Depth range: 1240 - 2329 m, living: 1240 m.

Occurrence: Occurs at only two stations.

Subfamily OOLININAE

Oolina spp.

Remarks: As with Lagena and Lenticulina it was found difficult to assign many specimens to recognised species. Those species that definitely occur are listed below.

Occurrence: Most specimens on the shelf are O. melo, those on the slope are referred to many species.

Oolina apicularis Reuss

Brady 1884, pl. 56, fig. 15.

Occurrence: Rare, on outer shelf.

Oolina botelliformis (Brady)

Brady 1884, pl. 56, fig. 6.

Occurrence: Rare, on lower slope.

Oolina felsinea (Fornasini)

Brady 1884, pl. 56, fig. 4.

Occurrence: Rare, on lower slope.

Oolina globosa (Montague)

Brady 1884, pl. 56, figs 1 - 3.

Occurrence: Ubiquitous but rare.

Oolina hexagona (Williamson)

Loeblich and Tappan 1953, pl. 14, figs 1, 2.

Occurrence: Rare, on shelf, upper slope and bank.

Oolina melo d'Orbigny

Loeblich and Tappan 1953, pl. 12, figs 8 - 15.

Occurrence: Common on inner shelf, fairly common on outer shelf and rare on upper slope.

Oolina ovum (Ehrenburg)

Brady 1884, pl. 56. fig. 5.

Occurrence: Rare, on lower slope.

Fissurina spp.

Remarks: Many specimens of Fissurina could not be assigned to known species but those species that were recognised are listed below.

Fissurina annectens (Burrows and Holland)

Brady 1884, pl. 59, fig. 15.

Occurrence: Ubiquitous but rare at any station.

Fissurina clathrata (Brady)

Brady 1884, pl. 60, fig. 4.

Occurrence: Rare, at many stations from inner shelf to mid slope.

Fissurina crebra (Matthes)

Brady 1884, pl. 59, fig. 6.

Occurrence: Rare, on upper slope.

Fissurina aff. *cucullata* Silvestri

Brady 1884, pl. 59, fig. 25.

Occurrence: Rare, on upper slope.

Fissurina earlandi Parr

Occurrence: Ubiquitous but rare.

Fissurina kerguelensis Parr

Brady 1884, pl. 59, figs 8, 9.

Occurrence: Ubiquitous but rare.

Fissurina laevigata Reuss

Brady 1884, pl. 114, fig. 8.

Occurrence: Rare, on slope.

Fissurina lucida (Williamson)

Occurrence: Ubiquitous, fairly common on shelf.

Fissurina aff. *orbignyana* Seguenza

Brady 1884, pl. 59, fig. 18.

Occurrence: Rare, on lower slope.

Fissurina revertens (Heron-Allen and Earland)

Heron-Allen and Earland 1932, pl. 11, figs 26 - 28.

Occurrence: Ubiquitous but rare.

Fissurina squamoso-marginata (Parker and Jones)

Brady 1884, pl. 60, fig. 24.

Occurrence: Rare, on mid slope.

Fissurina submarginata (Boomgart)

Brady 1884, pl. 59, fig. 22.

Occurrence: Rare, on upper slope.

Fissurina unguiculata (Brady)

Brady 1884, pl. 59, fig. 12.

Occurrence: Rare, on upper slope.

Parafissurina spp.

Remarks: Some specimens of *Parafissurina* could not be assigned to known species. Those species that were recognised are listed below.

Parafissurina curta Parr

Occurrence: Rare, on slope.

Parafissurina quadrata Parr

Occurrence: Rare, on lower slope.

Parafissurina ventricosa (Silvestri)

Loeblich and Tappan 1964, fig. 425, no. 9.

Occurrence: Rare, on lower slope.

Superfamily BULIMINACEA

Family TURRILINIDAE

Subfamily TURRILININAE

Buliminella madagascariensis (d'Orbigny)

Cushman and Parker 1947, pl. 17, figs 15 - 18.

Length: 0.15 - 0.35 mm.

Depth range: 18 - 625 m, no living specimens.

Occurrence: Rare, at only two stations.

Family SPHAEROIDINIDAE

Sphaeroidina bulloides d'Orbigny

Brady 1884, pl. 84, figs 1, 2.

Remarks: The difference between S. bulloides and S. compressa is not clear so all specimens are referred to the first described species; wall of most specimens is translucent.

Length: 0.18 - 0.53 mm.

Depth range: 18 - 2432 m, living: 42 - 2063 m.

Occurrence: Common everywhere except inner shelf, most common on outer shelf and on bank.

Family BOLIVINITIDAE

Bolivinita quadrilaterata (Schwager)

Brady 1884, pl. 42, figs 8 - 12.

Length: 0.35 - 0.95 mm.

Depth range: 48 - 2469 m, living: 1419 m.

Occurrence: Moderately common on mid and lower slope.

Bolivina pseudo-plicata Heron-Allen and Earland

Length: 0.15 - 0.30 mm, width: 0.10 - 0.13 mm.

Depth range: 18 - 1649 m, living: 48 - 375 m.

Occurrence: Common from inner shelf to mid slope.

Bolivina robusta Brady

Brady 1884, pl. 53, figs 7 - 9.

Length: 0.20 - 0.45 mm, width: 0.15 - 0.22 mm.

Depth range: 18 - 1649 m, living: 186 - 375 m.

Occurrence: Moderately common shelf, abundant on banks, common on upper and mid slope.

Bolivina sphenoides Chapman and Parr

Remarks: Specimens were compared with topotype material; there is no adequate figure of this species; it is quadrilateral in apertural view and has raised crenulate sutures.

Length: 0.14 - 0.35 mm, width: 0.11 - 0.19 mm.

Depth range: 375 - 2469 m, living: 1240 - 1649 m.

Occurrence: Abundant on mid slope, common on lower slope.

Bolivina ? sp.

Remarks: Has areal aperture so is not typical of the genus Bolivina; test oval in apertual view, side view varies from moderately flaring to almost parallel sided. Chambers with retral processes similar to those of B. pseudo-plicata; aperture areal with lip; large internal tooth plate.

Length: 0.24 - 0.36 mm.

Depth range: 42 - 479 m, living: 42 - 329 m.

Occurrence: Abundant on bank, rare elsewhere.

Brizalina alata (Seguenza)

Brady 1884, pl. 53, figs 2, 3.

Length: About 0.7 mm.

Depth range: 329 - 1649 m, no living specimens.

Occurrence: Rare.

Brizaline cacozela Vella

Remarks: More rounded periphery than B. spathulata and usually narrower.

Length: 0.20 - 0.45 mm, width: 0.08 - 0.14 mm.

Depth range: 18 - 2469 m, living: 18 - 1240 m.

Occurrence: Common, most common on outer shelf and bank.

Brizalina earlandi Parr

Length: 0.12 - 0.48 mm.

Depth range: 91 - 2469 m, living: 375 - 2432 m.

Occurrence: Common only on mid and lower slope.

Brizalina spathulata (Williamson)

Hedley et al 1965, pl. 6, fig. 22, text-fig. 6.

Remarks: Distinctly more carinate than B. cacozela and usually more flaring.

Length: 0.25 - 0.49 mm.

Depth range: 18 - 2432 m, living: 48 - 71 m.

Occurrence: Fairly common on shelf to 71m, a few dead specimens on lower slope.

Brizalina aff. subspinescens (Cushman)

Remarks: Pustulose lower part of each chamber, aperture broad, loop-shaped partly closed by plate formed by incurved part of apertural face; initial growth tends to be twisted; may be referable to genus Laterostomella or perhaps to Stainforthia.

Length: 0.15 - 0.46 mm.

Depth range: 130 - 2329 m, living: 130 m.

Occurrence: Common from outer shelf to mid slope.

Brizalina ? kerreriana (Brady)

Brady 1884, pl. 53, figs 19 - 21.

Remarks: Hedley et al (1967) noted that this species has a radial wall structure and belongs with the

Bolivinidae. However, its areal aperture is not typical of the genus Brizalina.

Length: 0.28 - 0.80 mm.

Depth range: 40 - 1419 m, living: 40 - 427 m.

Occurrence: Common or abundant on outer shelf and upper slope, rare elsewhere.

Rectobolivina columellaris (Brady)

Brady 1884, pl. 75, figs 15 - 17.

Length: 0.67 - 0.92 mm, width: 0.20 - 0.22 mm.

Depth range: 329 m, no living specimens.

Occurrence: Moderately common on bank.

Family BULIMINIDAE

Subfamily BULIMININAE

Bulimina aculeata d'Orbigny

Brady 1884, pl. 51, figs 7 - 9.

Length (without basal spine): 0.2 - 0.7 mm.

Depth range: 180 - 2469 m, living: 276 - 2469 m.

Occurrence: Abundant and living at almost every station on slope.

Bulimina marginata d'Orbigny

Hedley *et al* 1965, text-fig. 5.

Length: 0.15 - 0.55 mm.

Depth range: 18 - 625 m, living: 40 - 427 m.

Occurrence: Common on shelf and upper slope, range overlaps with that of B. aculeata on upper slope.

Bulimina nipponica Asano

Brady 1884, pl. 5, figs 11 - 13.

Remarks: Brady's figures are not B. costata, which does not have spines.

Length: 0.20 - 0.93 mm but mostly about 0.4 - 0.5 mm.

Depth range: 18 - 2469 m, living: 186 - 2329 m.

Occurrence: Moderately common everywhere.

Bulimina rostrata Brady

Cushman and Parker 1947, pl. 28, fig. 34.

Remarks: Similar to B. truncanella.

Length: 0.24 - 0.28 mm.

Depth range: 1240 - 2432 m, living: 1240 - 1419 m.

Occurrence: Common on mid slope, rare on lower slope.

Globobulimina turgida (Bailey)

Hedley et al 1965, pl. 7, fig. 26; Höglund 1947, pl. 21, figs 4, 8, text-figs 247 - 257.

Length: 0.4 - 0.8 mm.

Depth range: 113 - 375 m, living: 186 - 304 m.

Occurrence: Fairly common on outer shelf and upper slope.

Globobulimina hoeglundi Uchio

Höglund 1947, text-figs 243 - 246.

Length: 0.32 - 0.80 mm.

Depth range: 276 - 2469 m, living: 276 - 2028 m.

Occurrence: Common on bank and at some stations on upper slope.

Globobulimina notovata (Chapman)

Brady 1884, pl. 50, figs 9, 13.

Length: 0.38 - 1.00 mm.

Depth range: 186 - 2469 m, living: 276 - 2469 m.

Occurrence: Common everywhere on slope.

Globobulimina cf. pacifica Cushman

cf. Brady 1884, pl. 50, fig. 10.

Remarks: Narrow, almost parallel sided with all chambers extending to base; three chambers form exterior surface; wall transparent to translucent.

Length: 0.45 - 0.57 mm, width: 0.18 - 0.27 mm.

Depth range: 186 - 2432 m, living: 1649 - 2329 m.

Occurrence: Moderately common on mid and lower slope.

Praeglobulimina spinescens (Brady)

Loeblich and Tappan 1964, fig. 442, nos 12, 13.

Length: 0.22 - 0.53 mm.

Depth range: 130 - 1419 m, living: 276 - 479 m.

Occurrence: Moderately common on upper slope.

Stainforthia concava (Höglund)

Loeblich and Tappan 1964, fig. 442, nos 10, 11.

Remarks: Specimens have been compared with a single, damaged, topotype specimen of Virgulina davisi and appear to have more inflated chambers. However, as pointed out by Höglund, the original description and figures of V. davisi are completely inadequate.

Length: 0.20 - 0.40 mm.

Depth range: 329 - 2432 m, living: 2329 - 2432 m.

Occurrence: Common at most places on slope, most common on mid and lower slope.

Stainforthia sp.

Remarks: Test small, fusiform, chambers in twisted biserial arrangement. Aperture and apertural face similar to S. concava but relatively smaller.

Length: 0.36 - 0.42 mm, width: 0.10 - 0.11 mm.

Depth range: 91 - 2329 m, living: 91 - 1649 m.

Occurrence: Common on mid slope, and at some stations elsewhere.

Family UVIGERINIDAE

Euuvigerina peregrina (Cushman)

Brady 1884, pl. 74, figs 11, 12.

Remarks: Many specimens have ridges on final chamber broken up into spines; some have long spines near proximal edge.

Length: 0.3 - 1.1 mm.

Depth range: 18 - 2469 m, living: 276 - 2329 m.

Occurrence: Single specimen on shelf, abundant on upper slope and bank, common on mid and lower slope.

Hopkinsina pacifica Cushman

Remarks: Immature specimens do not have an areal aperture but have a Bulimina-type slit.

Length: 0.18 - 0.38 mm.

Depth range: 91 - 1241 m, living: 91 - 479 m.

Occurrence: Common from outer shelf to mid slope.

Siphouvigerina asperula (Czjek)

Brady 1884, pl. 75, figs 6, 7, 8.

Length: 0.23 - 0.63 mm.

Depth range: 48 - 2432 m, living: 186 m.

Occurrence: Ubiquitous but common only on bank.

Siphouvigerina interrupta (Brady)

Brady 1884, pl. 75, figs 12 - 14.

Length: 0.42 - 0.65 mm.

Depth range: 186 - 1240 m, living: 186 - 375 m.

Occurrance: Abundant on bank, common on upper slope.

Trifarina angulosa (Williamson)

Brady 1884, pl. 74, figs 15, 16.

Length: 0.12 - 0.29 mm.

Depth range: 18 - 2432 m, living: 329 - 2329 m.

Occurrence: Common slope, abundant on bank.

Trifarina bradyi Cushman

Brady 1884, pl. 67, figs 1 - 3.

Length: About 0.4 mm.

Depth range: 18 - 1240 m, no living specimens.

Occurrence: Common on bank, rare elsewhere.

Trifarina gracilis Vella

Length: About 0.4 mm.

Depth range: 71 - 91 m, no living specimens.

Occurrence: Rare.

Virgulinopsis turris (Heron-Allen and Earland)

Hedley *et al* 1967, pl. 9, fig. 5.

Length: 0.09 - 0.25 mm.

Depth range: 18 - 625 m, living: 18 m.

Occurrence: Common on shelf, single dead specimen from lower slope, large living population at shallowest station.

Superfamily DISCORBACEA

Family DISCORBIDAE

Subfamily DISCORBINAE

Discorbis dimidiatus (Jones and Parker)

Hedley et al 1967, text-figs 28 - 43.

Length: 0.25 - 0.72 mm.

Depth range: 18 - 130 m, living: 18 - 40 m.

Occurrence: Common on inner shelf.

Discorbinella cf. bertheloti (d'Orbigny)

cf. Loeblich and Tappan 1964, fig. 453, no. 3.

Remarks: Domed side more involute than Loeblich and Tappan's figure; some specimens tend towards shape of D. baconica var. baconica as illustrated by Brady 1884, pl. 90, fig. 1; conspicuous umbilical chamber flaps.

Length: 0.28 - 0.48 mm.

Depth range: 40 - 479 m, living: 276 - 375 m.

Occurrence: Rare on shelf, common on bank and upper slope.

Epistominella exigua (Brady)

Remarks: Many specimens have more globose chambers and less angular periphery than type figures (Brady 1884, pl. 10, figs 13, 14); all have conspicuous slit extending from base of apertural face towards periphery.

Length: 0.10 - 0.27 mm.

Depth range: 18 - 2469 m, living: 18 - 2469 m.

Occurrence: Abundant on outer shelf, common elsewhere.

Gavelinopsis hamatus Vella

Length: 0.17 - 0.50 mm.

Depth range: 18 - 1419 m, living: 18 - 42 m.

Occurrence: Common on inner shelf and on bank, rare elsewhere; occurs where sediment most coarse.

Gavelinopsis lobatulus Parr

Brady 1884, pl. 88, fig. 1.

Length: 0.13 - 0.41 mm.

Depth range: 130 - 1419 m, living: 186 - 1240 m.

Occurrence: Common on bank, upper slope and mid slope.

Laticarinina altocamerata (Heron-Allen and Earland)

Brady 1884, pl. 93, fig. 2.

Length: 0.3 - 0.4 mm.

Depth range: 329 - 1649 m, no living specimens.

Occurrence: Common on bank, rare on upper and mid slope.

Laticarinina pauperata (Parker and Jones)

Brady 1884, pl. 104, figs 3 - 11; Eade 1967, frontispiece.

Length: About 1 - 2 mm.

Depth range: 1649 - 2432 m, no living specimens.

Occurrence: Moderately common at three stations only.

Planodiscorbis rarescens (Brady)

Length: 0.3 - 0.7 mm.

Depth range: 329 - 1419 m, no living specimens.

Occurrence: Common on bank, rare on slope.

Rosalina bradyi (Cushman)

Hedley et al 1967, fig. 2, text-figs 50-55.

Length: 0.18 - 0.55 mm.

Depth range: 18 - 276 m, living: 18 - 130 m.

Occurrence: Common on shelf, most common on inner shelf.

Rosalina irregularis (Rhumbler)

Hedley et al 1967, pl. 11, fig. 3.

Length: 0.20 - 0.45 mm.

Depth range: 18 - 48 m, living: 18 - 42 m.

Occurrence: Common, on inner shelf.

Rosalina paupereques Vella

Length: 0.27 mm.

Depth range: 71 m, no living specimens.

Occurrence: Rare.

Subfamily BAGGININAE

Cancris maoricus Finlay

Length: 0.6 - 1.5 mm.

Depth range: 329 m, no living specimens.

Occurrence: Common bank.

Valvulineria aff. laevigata Phleger and Parker

Remarks: Test more flaring and apertural flaps larger than V. laevigata.

Length: 0.24 - 0.30 mm.

Depth range: 375 - 2329 m, living: 479 - 2329 m.

Occurrence: Common on upper and mid slope, rare on lower slope.

Family GLABRATELLIDAE

Glabratella radiata (Vella)

Length: 0.27 - 0.52 mm.

Depth range: 18 - 48 m, no living specimens.

Occurrence: Common on inner shelf.

Glabratella zealandica (Vella)

Length: 0.17 - 0.37 mm.

Depth range: 18 - 71 m, no living specimens.

Occurrence: Common on inner shelf.

Family SIPHONINIDAE

Siphonina cf. tubulosa (Cushman)

Brady 1884, pl. 96, figs 5 - 7.

Remarks: Filled keel not as well developed as in Brady's figures; shell opaque.

Length: 0.43 - 0.60 mm.

Depth range: 329 m, no living specimens.

Occurrence: Common, on bank only.

Superfamily SPIRILLINACEA

Family SPIRILLINIDAE

Subfamily SPIRILLININAE

Spirillina obconica Brady

Brady 1884, pl. 85, fig. 6.

Length: 0.25 mm.

Depth range: 42 m, no living specimens.

Occurrence: Rare, at single station only.

Spirillina vivipara Ehrenberg

Brady 1884, pl. 85, fig. 2.

Length: 0.15 - 0.20 mm.

Depth range: 40 - 2469 m, living: 42 m.

Occurrence: A few specimens on inner shelf and single specimen on lower slope.

Superfamily ROTALIACEA

Family ROTALIIDAE

Subfamily ROTALIINAE

Ammonia aoteanus (Finlay)

Hedley et al 1967, pl. 11, fig. 4, text-figs 56 - 60.

Length: 0.3 - 0.7 mm.

Depth range: 18 - 276 m, living: 18 - 48 m.

Occurrence: Fairly common on inner shelf, rare elsewhere.

Family ELPHIDIIDAE

Subfamily ELPHIDIINAE

Elphidium novo-zealandicum Cushman

Hedley et al 1967, pl. 12, fig. 4.

Length: 0.20 - 0.85 mm.

Depth range: 18 - 71 m, no living specimens.

Occurrence: Common on inner shelf.

Cribrononion argenteum (Parr)

Hedley *et al* 1967, pl. 12, fig. 2.

Length: 0.20 - 0.38 mm.

Depth range: 40 - 625 m, living: 48 - 427 m.

Occurrence: Common on outer shelf, rare elsewhere.

Cribrononion charlottensis (Vella)

Hedley *et al* 1967, pl. 12, fig. 3.

Length: 0.2 - 0.5 mm.

Depth range: 18 - 2469 m, living: 18 - 130 m.

Occurrence: Common on shelf, a few dead specimens on slope.

Cribrononion simplex (Cushman)

Hedley *et al* 1967, pl. 12, fig. 1.

Length: 0.15 - 0.45 mm.

Depth range: 18 - 2028 m, living: 18 - 48 m.

Occurrence: Common on shelf at depths of less than 71 m, rare elsewhere.

Subfamily FAUJASININAE

Notorotalia aucklandica Vella

Length: 0.4 - 0.7 mm.

Depth range: 40 - 304 m, no living specimens.

Occurrence: Rare.

Notorotalia clathrata (Brady)

Length: 0.5 - 0.7 mm.

Depth range: 40 - 42 m, living: 42 m.

Occurrence: Rare.

Notorotalia finlayi Vella

Length: 0.20 - 0.45 mm.

Depth range: 40 - 1240 m, living: 48 - 427 m.

Occurrence: Common on outer shelf and upper slope.

Notorotalia inornata Vella

Length: 0.35 - 0.60 mm.

Depth range: 18 - 479 m, no living specimens.

Occurrence: Rare.

Notorotalia profunda Vella

Length: 0.2 - 0.6 mm, mainly about 0.35 mm.

Depth range: 18 - 625 m, living: 91 - 329 m.

Occurrence: Rare on shelf, common on upper slope, abundant on bank.

Notorotalia zealandica Finlay

Vella 1957, pl. 2, figs 31, 33, 34.

Length: 0.3 - 1.1 mm.

Depth range: 40 - 625 m, living: 40 - 186 m.

Occurrence: Common on shelf, rare on upper slope.

Superfamily ORBITOIDACEA

Family EPONIDIDAE

Eponides pusillus Parr

Length: 0.11 - 0.21 mm.

Depth range: 18 - 2432 m, living: 48 - 1240 m.

Occurrence: Rare on shelf, very common on slope, abundant on bank.

Eponides tumidulus (Brady)

Brady 1884, pl. 95, fig. 8.

Remarks: Small but with more globose chambers than *E. pusillus*.

Length: 0.10 - 0.12 mm.

Depth range: 329 - 1649 m, living: 1649 m.

Occurrence: Rare.

Family CIBICIDADEA

Subfamily PLANULININAE

Planulina aff. *arimiensis* d'Orbigny

Remarks: Has more pronounced apertural flaps than *P. ariminensis* (Loeblich and Tappan 1964, fig. 552, no. 1)

Length: About 0.35 mm.

Depth range: 304 - 1419 m, living: 375 m.

Occurrence: Common on banks, rare on slope.

Subfamily CIBICIDINAE

Cibicides ihungia Finlay

Length: About 0.5 mm.

Depth range: 329 - 2063 m, no living specimens.

Occurrence: Common on upper slope, rare elsewhere.

Cibicides marlboroughensis Vella

Remarks: Final chambers are added more loosely than early chambers so that some large specimens resemble *C. delicata* although *C. delicata* is generally flatter than large specimens of *C. marlboroughensis*.

Length: 0.17 - 0.70 mm.

Depth range: 18 - 2469 m, living: 18 - 304 m.

Occurrence: Common on shelf and upper slope, abundant on bank, moderately common on mid and lower slope.

Cibicides wuellerstorfi (Schwager)

Brady 1884, pl. 93, fig. 9.

Length: 0.3 - 0.7 mm.

Depth range: 304 - 2329 m, no living specimens.

Occurrence: Common on slope and bank.

Dyocibicides primitiva Vella

Remarks: Early coil similar to small *C. marlboroughensis*.

Length: 0.2 - 0.8 mm.

Depth range: 18 - 1419 m, living: 42 m.

Occurrence: Moderately common on inner shelf and bank, rare elsewhere, may be confined to places where suitable rock or shelf substrate present.

Family CAUCASINIDAE

Subfamily FURSENKOININAE

Fursenkoina rotundata Parr

Brady 1884, pl. 52, figs 10, 11.

Length: 0.38 - 0.62 mm.

Depth range: 276 - 2432 m, living: 479 - 1240 m.

Occurrence: Common on upper and mid slope.

Fursenkoina squammosa (d'Orbigny)

Loeblich and Tappan 1964, fig. 600, nos 1 - 4.

Length: 0.35 - 1.08 mm.

Depth range: 186 - 479 m, living: 186 - 479 m.

Occurrence: Common on upper slope.

Family CASSIDULINIDAE

Cassidulina carinata Silvestri

Hedley et al 1967, pl. 12, fig. 6; Eade 1967, fig. 2, nos 5 - 9.

Length: 0.11 - 0.30 mm.

Depth range: 18 - 2469 m, living: 40 - 1649 m.

Occurrence: Ubiquitous, abundant on bank and at places on upper and mid slope, common everywhere else.

Ehrenbergina mestayeri Cushman

Eade 1967, fig. 8, nos 6, 7.

Remarks: Specimens from Madden Banks do not have spines around margin and may have been eroded from Tertiary mudstone.

Length: 0.4.- 0.7 mm.

Depth range: 18 - 329 m, no living specimens.

Occurrence: Occurs where sediment relatively coarse.

Evolvocassidulina orientalis (Cushman)

Eade 1967, fig. 4, nos 1, 2; Hedley *et al* 1967, pl. 12, fig. 5.

Length: 0.2 - 0.5 mm.

Depth range: 18 - 2469 m, living: 40 - 479 m.

Occurrence: Common on shelf, very common on upper slope, abundant on bank, moderately common on mid slope, rare on lower slope.

Globocassidulina canalisuturata Eade

Eade 1967, fig. 3, nos 5 - 7, fig. 5, nos 7 - 8.

Length: 0.35 - 0.55 mm.

Depth range: 142 - 479 m, no living specimens.

Occurrence: Abundant on bank and on Madden Banks.

Globocassidulina aff. inflata (Le Roy)

Eade 1967, fig. 4, no. 3.

Length: 0.10 - 0.22 mm.

Depth range: 18 - 2469 m, living: 130 - 2329 m.

Occurrence: Common at many stations, absent at others.

Globocassidulina minuta (Cushman)

Eade 1967, fig. 5, nos 2, 3.

Length: 0.2 - 0.3 mm.

Depth range: 329 - 2469 m, living: 329 m.

Occurrence: Common on bank, common at one station on mid slope, rare elsewhere.

Globocassidulina producta (Chapman and Parr)

Eade 1967, fig. 4, no. 5.

Length: 0.17 - 0.53 mm.

Depth range: 18 - 2469 m, living: 130 m.

Occurrence: Common on bank and on mid and lower slope, rare elsewhere.

Globocassidulina spherica Eade

Eade 1967, fig. 7, nos 1 - 3.

Length: 0.2 - 0.5 mm.

Depth range: 18 - 91 m, no living specimens.

Family NONIONIDAE

Subfamily CHILOSTOMELLINAE

Chilostomella cushmani Chapman

Brady 1884, pl. 56, fig. 13.

Length: 0.20 - 0.75 mm, width: 0.08 - 0.47 mm.

Depth range: 18 - 2063 m, living: 115 - 479 m.

Occurrence: Common on upper slope, rare elsewhere.

Chilostomella cf. *oolina* Schwager

Brady 1884, pl. 55, figs 14, 17

Remarks: Almost parallel sides and bluntly rounded ends.

Length: 0.40 - 0.85 mm, width: 0.17 - 0.40 mm.

Depth range: 479 - 2469 m, living: 479 - 1649 m.

Occurrence: Common on mid and lower slope, generally deeper than *C. cushmani*.

Subfamily NONIONIDAE

Astrononion novozealandicum Cushman and Edwards

Hedley *et al* 1965, pl. 7, fig. 28.

Remarks: Small specimens have less distinct sutures than large specimens.

Length: 0.20 - 0.47 mm.

Depth range: 18 - 2028 m, living: 40 - 2028 m.

Occurrence: Moderately common on shelf, common on upper and mid slope, abundant on bank.

Astrononion cf. tumidum Cushman and Edwards

cf. Brady 1884, pl. 109, fig. 5.

Remarks: Small with about 6 - 7 chambers in final whorl, early sutures not as deep as in Brady's figures.

Length: 0.25 - 0.30 mm.

Depth range: 91 - 2432 m, living: 91 m.

Occurrence: Common on bank, rare elsewhere.

Florilus scaphum (Fichtel and Moll)

Brady 1884, pl. 109, figs 14, 15.

Length: 0.2 - 0.3 mm.

Depth range: 479 - 1419 m, no living specimens.

Occurrence: Common on bank and upper slope.

Nonionella bradyi (Chapman)

Brady 1884, pl. 109, fig. 16.

Length: 0.2 - 0.3 mm.

Depth range: 276 - 2329 m, living: 2028 - 2329 m.

Occurrence: Common at some stations on slope.

Nonionella aff. translucens Cushman

Remarks: Small, very thin and translucent wall, 6 - 7 globose chambers in final whork, sutures deep.

Length: 0.12 - 0.25 mm.

Depth range: 91 - 2432 m, living: 91 - 2432 m.

Occurrence: Common only on mid and lower slope.

Nonionella turgida (Williamson)

Brady 1884, pl. 109, figs 17 - 19; Cushman 1939, pl. 9, figs 2, 3.

Remarks: Some specimens have an inflated final chamber that droops down over the umbilical area on one side.

Length: 0.12 - 0.42 mm.

Depth range: 40 - 2063 m, living: 40 - 1419 m.

Occurrence: Common at all stations from outer shelf to mid slope.

Nonionellina flemingi (Vella)

Lewis and Jenkins 1969, pl. 1, figs 1 - 9.

Length: 0.14 - 0.38 mm.

Depth range: 40 - 2469 m, living: 40 - 625 m.

Occurrence: On shelf, very common both living and dead except at two shallowest stations; on upper slope and bank very common but fewer living specimens; moderately common on lower slope but no living specimens.

Pullenia bulloides d'Orbigny

Brady 1884, pl. 84, fig. 12, 13.

Length: 0.16 - 0.23 mm.

Depth range: 1240 - 2469 m, living: 1419 - 2432 m.

Occurrence: Common on mid and lower slope.

Pullenia subcarinata (d'Orbigny)

Brady 1884, pl. 84, fig. 14.

Length: 0.22 - 0.40 mm.

Depth range: 18 - 2469 m, living: 329 - 2432 m.

Occurrence: Rare on shelf, common on slope.

Zeaflorilus parri (Cushman)

Cushman 1939, pl. 9, fig. 12.

Length: 0.20 - 0.65 mm.

Depth range: 18 - 625 m, living: 18 - 48 m.

Occurrence: Very common both living and dead on inner shelf, moderately common on outer shelf and rare on upper slope.

Family ALABAMINIDAE

Gyroidina orbicularis d'Orbigny

Brady 1884, pl. 115, fig. 6.

Remarks: Much smaller and much more compressed than Gyroidinoides neosoldanii, sutures recurved in immature specimens and almost radial in adults.

Length: 0.21 - 0.45 mm.

Depth range: 18 - 2432 m, living: 375 - 1649 m.

Occurrence: Common everywhere.

Oridorsalis tenera (Brady)

Brady 1884, pl. 95, fig. 11.

Length: 0.18 - 0.46 mm.

Depth range: 71 - 2329 m, living: 71 - 2329 m.

Occurrence: Common from outer shelf to mid slope, abundant on bank.

Family OSANGULARIDAE

Osangularia bengalensis (Schwager)

Brady 1884, pl. 96, fig. 3.

Length: 0.25 - 0.55 mm.

Depth range: 1240 - 2329 m, living: 1240 - 2329 m.

Occurrence: Common, on mid and lower slope.

Osangularia sp.

Remarks: Smaller and more thin-walled than O. bengalensis; keel not frilled and sutures curved.

Length: 0.22 - 0.34 mm.

Depth range: 625 - 2329 m, no living specimens.

Occurrence: Rare, on slope.

Gyroidinoides neosoldanii (Brotzen)

Brady 1884, pl. 107, fig. 6.

Length: 0.6 - 1.1 mm.

Depth range: 48 - 2329 m, living: 2329 m.

Occurrence: A few specimens at many stations.

Family ANOMALINIDAE

Subfamily ANOMALININAE

Anomalinoides nipponicus (Ishizaki)

Remarks: Original description as *Gyroidina*.

Length: 0.10 - 0.29 mm.

Depth range: 40 - 1439 m, living: 91 - 625 m.

Occurrence: Moderately common on outer shelf and upper slope, very common on bank.

Anomalinoides spherica (Finlay)

Remarks: Many specimens are involute on the spiral side and more compressed than typical *A. sherica*, they closely resemble *A. pinguiglabra*.

Length: 0.25 - 0.50 mm.

Depth range: 18 - 375 m, living: 40 - 71 m.

Occurrence: Common on shelf, rare on upper slope.

Anomalinoides sp.

Remarks: Smaller and more compressed than *A. nipponicus*.

Length: 0.09 - 0.21 mm.

Depth range: 18 - 2432 m, living: 375 - 1240 m.

Occurrence: Common on upper slope, moderately common elsewhere.

Heterolepa aff. *dutemplei* (d'Orbigny)

Remarks: Size, shape and wall structure as *H. dutemplei* in Loeblich and Tappan 1964, fig. 623, no. 3, but with supplementary aperture at proximal, peripheral margin of final chamber, one specimen has stained protoplasm streaming from primary and supplementary aperture and is partially covered with sand grains.

Length: 0.6 - 1.5 mm.

Depth range: 186 - 625 m, living: 625 m.

Occurrence: Common on bank, rare elsewhere.

Melonis cf. *barleeanum* (Williamson)

cf. Brady 1884, pl. 109, fig. 8.

Remarks: Less open umbilicus than Brady's figure.

Length: 0.2 - 0.5 mm.

Depth range: 479 - 2469 m, living: 1240 m.

Occurrence: Common on mid and lower slope.

Melonis sphaeroides Voloshinova

Brady 1884, pl. 109, figs 10, 11.

Remarks: Voloshinova suggested retaining the name *M. pompiloides* for Albanian, Pliocene specimens and proposed the name *M. sphaeroides* for more globose, more coarsely perforate, Recent specimens

Length: About 0.25 mm.

Depth range: 2469 m, no living specimens.

Occurrence: Rare, only at deepest station.

Superfamily ROBERTINACEA

Family CERATOBULIMINIDAE

Subfamily EPISTOMININAE

Hoeglundina elegans (d'Orbigny)

Brady 1884, pl. 105, figs 3 - 5.

Length: 0.5 - 1.0 mm.

Depth range: 113 - 2469 m, living: 113 - 375 m.

Occurrence: A few specimens at many stations on outer shelf and on slope.

THE FORAMINIFERAL FAUNA

The abundance of benthonic foraminifera in each sample is a function of the rate of reproduction, preservation of empty tests and dilution by other sediment. The abundance of benthonic foraminifera in 17 ml of wet sediment ranges from 400-110,000 specimens (Fig. 46a). Samples from the inner shelf contain less than 1000 specimens, most of the others contain 1000-6000 specimens. Benthonic foraminifera are most abundant on the bank where dilution by detrital sediment is minimal and they are least abundant on the inner shelf where there is a relatively large input of detrital sediment, where fragile tests are likely to be destroyed by turbulence and where food is likely to be scarce. The number of specimens in 10 ml of sediment, a measure used commonly in distributional studies (Phleger 1960) is shown by the scale on the right of Fig. 46a.

The number of living foraminifera on a surface area of 1700 mm^2 ranges from 17-585 specimens (Fig. 46a). Largest numbers occur on the

FIGURE CAPTION

FIGURE 46.

Frequency polygons showing abundance of benthonic foraminiferal fauna at each station. A. Numbers of specimens in 17 ml of wet sediment, broken line is numbers of living specimens; scale at right shows number of specimens in 10 ml of wet sediment. B. number of species at each station, broken line is number of species that were living at each station.

continental shelf at depths of 48-130m : Walton (1955) found the largest number at depths of 36-91m on the shelf off Mexico. The smallest numbers occur on the innermost part of the continental shelf and on the lower slope. Samples were collected in November when the number of living specimens on the continental shelf might be expected to be less than later in the summer (Walton 1955). The "standing crop" of foraminifera is commonly expressed as the living population per square metre of seabed (Phleger 1960). Values in the study area range from 10,000-350,000/m^2. These are high compared with abundances of 1,000-100,000/m^2 in the Gulf of Maine but comparable with an average of 90,000/m^2 at the Mississippi Delta. The living population of benthonic foraminifera is a partial measure of productivity which is apparently relatively high in the study area.

The number of species, living and dead, per sample increases from the inner shelf to a maximum on the mid slope (Fig. 46b) : i.e. the benthonic foraminiferal population is more diverse on the continental slope than on the shelf. The number of species that are living at each station shows a similar but less marked trend.

Planktonic foraminifera are rare on the continental shelf (Fig. 47a) except at two stations (No. 1 and No. 3) where the majority of planktonic foraminifera are worn, broken and filled with sediment and are probably derived from Tertiary strata on the adjacent land or seabed. The majority of foraminiferal tests on the continental slope belong to planktonic species. It is uncertain whether this is due to slow accumulation of benthonic tests or to relatively rapid accumulation of planktonic tests. Planktonic foraminifera tend to sink during their life (Bé 1965) so that it is likely that more are deposited on the slope than on the shelf.

In the benthonic population the relative proportions of the three main suborders Textulariina, Miliolina and Rotaliina change with depth (Fig. 47b). At all depths Rotaliina are dominant but specimens of the suborder Miliolina are relatively common on the inner shelf and also

FIGURE CAPTION

FIGURE 47

Frequency polygon showing nature of foraminiferal fauna at each station. A. Percentage of planktonic specimens, B. Percentage of benthonic specimens in suborders Textulariina (stippled), Miliolina (black) and Rotaliina (white). Line shows percentage of benthonic specimens that are living at each station. C. Mean width, in millimetres, of living benthonic specimens (broken line), total benthonic population (solid line) and planktonic population (dotted line).

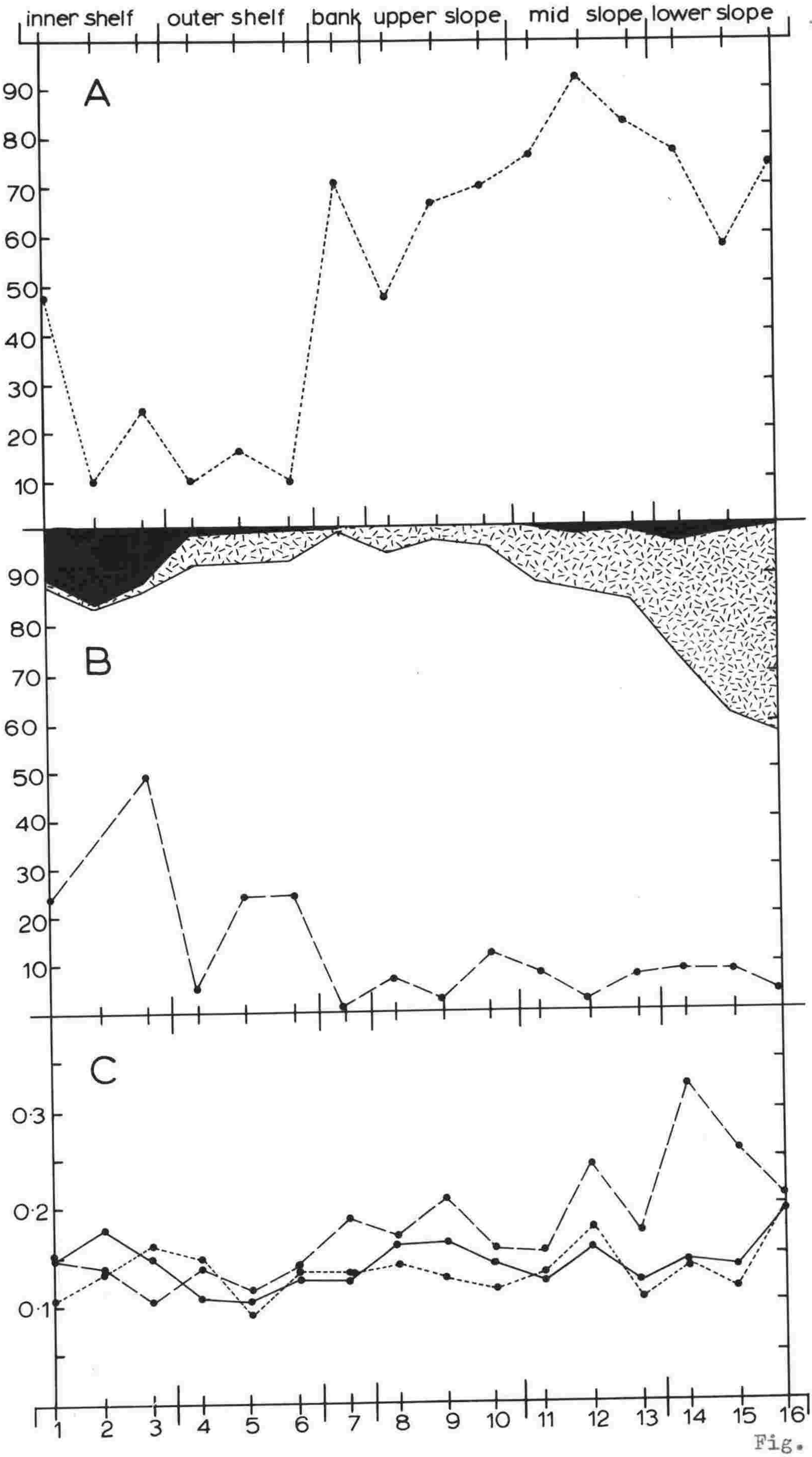
inner shelf
outer shelf
bank
upper slope
mid slope
lower slope
A
90
80
70
60
50
40
30
20
10
B
90
80
70
60
50
40
30
20
10
C
0·3
0·2
0·1
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Fig. 47

on the mid and lower slope where species are different from those on the inner shelf. Specimens of the suborder Textaluriina increase in abundance from 2% on the inner shelf to 43% on the lower slope.

Phleger (1955) showed that, at the Mississippi Delta, the percentage of living specimens in the benthonic population is, in general, directly proportional to the rate of deposition. In the present study area the percentage of living specimens in the benthonic population is, in general, higher on the shelf where deposition is relatively rapid than on the slope where deposition is relatively slow and it is least on the banks where deposition is almost zero.

The mean width of planktonic, total benthonic and living benthonic populations has been estimated at each station from the numbers in each sieve class (Fig. 47c). The mean width of planktonic and benthonic specimens ranges from 0.09-0.18mm and shows no marked trends with changes of depth. However, there appears to be a significant variation in the mean width of living specimens which are generally smaller than the total benthonic population on the inner shelf but larger elsewhere. The small size of specimens on the inner shelf may be a seasonal phenomenon : samples were collected in early summer when specimens are likely to be immature. The relatively large difference in size between living and dead populations on the continental slope may be partly a result of small dead specimens being transported downslope and thereby depressing the mean width of the total population, and partly a result of large agglutinated species that form a large part of the living population at some places tending to disintegrate on the death so that they are relatively rare in the total population.

BIOFACIES

The above study of individual species and total populations indicates that different environments have distinct foraminiferal faunas. It is seldom clear which environmental factors are controlling each part of the fauna.

The continental shelf (0-200 m) is characterised by - 1. a planktonic to benthonic ratio of less than 50%, 2. a benthonic foraminiferal fauna of less than 60 species. 3. a mean width of living specimens less than about 0.15 mm. Species that are common on the shelf and rare or absent on the slope include - *Ammonia aoteanus*, *Brizalina spathulata*, *Cribrononion* spp., *Elphidium novozealandium*, *Discorbis dimidiatus*, *Miliolinella subrotunda*, *Quinqueloculina* spp. (excluding *Q.* cf. *venusta* and *Q. wiesneri*), *Virgulopsis turris* and *Zeaflorilus parri*. Species that are common on the shelf and also occur on the upper slope include *Bulimina marginata*, *Nonionellina flemingi*, *Notorotalia finlayi* and *N. zelandica*.

The continental slope is characterised by 1. a planktonic to benthonic ratio of more than 50%, 2. a benthonic fauna of more than 60 species and 3. a living population with a mean width of more than 0.15 mm. Species that are common on most of the continental slope but rare or absent on the continental shelf include *Ammomarginulina* spp.

Ammosphaeroidina sphaeroidiniformis, *Bulimina aceuleata*, *Cibicides woellerstorfi*, *Cyclammina* spp. *Dentalina* spp., *Eponides pusillus*, *Euuvigerina peregrina*, *Globobulimina* spp., *Glomospira* spp., *Hormosina globulifera*, *Laticarinina* spp., *Melonis* cf *barleeanum*, *Nodosaria* spp., *Nonionella bradyi*, *Pyrgo murrhyna*, *Quinqueloculina wiesneri*, *Recurvoides* spp., *Saccammina* spp., *Seabrookia* spp., *Siphotextularia fretensis*, *Stainforthia concava*, *Valvulineria* aff. *laevigata*.

Different faunas of benthonic foraminifera characterise each of the five depth zones, the inner shelf, outer shelf, upper slope, mid slope and lower slope, as well as the banks on the continental slope. The distribution of most foraminifera appear to be controlled by some factor related to depth but a few occur only on a particular type of substrate regardless of depth.

Characteristic of the inner shelf are the species *Ammonia aoteanus*, *Cribrononion simplex*, *Discorbis dimidiatus*, *Elphidium novozealandicum*, *Glabratella* spp., *Massilina brodiei*, *Virgulinopsis turris* and *Zeaflorilus parri*.

The outer shelf is characterised by *Anomalinoides spherica*, *Cribrononion argenteum*, and the shallowest occurrence of many other species, notably *Oridorsalis tenera* and *Trochammina pusilla*. Many species are common on the outer shelf and on the upper slope including *Brizalina kerrerianum*, *Bulimina marginata*, *Cribrostomoides* sp., *Discorbinella* cf. *bertheloti*, *Hopkinsina pacifica*, *Nonionella turgida*, *Nonionellina flemingi*, *Notorotalia finlayi*, *Notorotalia profunda*, *Planularia tricarinella*, *Reophax scorpiurus*, *Saracenaria latifrons*, *Trochammina ochracea*.

On the upper slope the ranges of *Bulimina marginata* and *B. aculeata* overlap. Species that are common on the upper slope include those mentioned above as being common on the outer shelf and upper slope and *Chilostomella cushmani*, *Cibicides ihungia*, *Fursenkoina* spp., *Gavelinopsis lobatulus*, *Globobulimina turgida*, *G. hoeglundina*, *Praeglobobulimina spinescens*, *Siphouvigerina* spp.

The mid slope is characterised by many species that are rare or absent at shallower depths but which continue downslope to the lower slope. These include *Adercotryma glomeratum*, *Ammobaculites* spp., *Bathysiphon* spp., *Bolivina sphenoides*, *Bulimina rostrata*, *Chilostomella oolina*, *Eggerella bradyi*, *Globobulimina pacifica*, *Karreriella* spp., *Lagenammina difflugiformis*, *Osangularia bengalensis*, *Pelosina* spp., *Pullenia bulloides*, *Quinqueloculina* cf. *venusta*, *Reophax dentaliniformis*, *R.* aff. *guttifer*, *Rhizammina* spp., *Sigmoilinopsis schlumbergeri*, *Spiroplectammina* cf. *biformis*, *Storthosphaera albida*, *Thurammina* spp., *Trochammina* aff. *globigeriniformis*. Many of these species have agglutinated walls and belong to the suborder Textulariina which forms 10-20% of the benthonic foraminiferal fauna.

Only a few species are confined to the lower slope. These include *Aschemonella* spp., *Brachysiphon corbuliniformis*, *Discammina compressa*, *Lagenammina bulbosa*, *Melonis sphaeroides*, *Tolypammina vagans*. Specimens of several species of *Lagenammina* and *Rhizammina* are common and specimens of the suborder Textulariina constitute 28-43% of the benthonic foraminiferal fauna.

Banks on the continental slope have a fauna that includes most of the species occurring commonly at thesame depth as the bank, but also includes a few species that do not occur or are comparatively rare on the adjacent muddy slopes. At station No. 7 *Bolivina robusta* forms a large part of the benthonic fauna but also common are *Amphycoryna hirsuta*, *Astrononion* cf. *tumidum*, *Globocassidulina canalisuturalis*, *Laticarinina altocamerata*, *Marginulina* spp., *Marginulinopsis bradyi*, *Planodiscorbis rarescens*, *Ramulina globulifera*, *Rectobolivina columnellaris*, *Sigmoilopsis wanganuiensis*, *Siphonina* cf. *tubulosa*. At stations E and F on the Madden Banks the fauna includes *Pyrgo pisum*, *Quinqueloculina colleenae*, *Sigmomorphina lacrimosa*, *Siphonaperta crassa*, *Siphotextularia mestayeri* and *Triloculina trigonula*.

A few species appear to be correlated with a coarse substrate and occur on the inner shelf and on slope banks. These include *Dyocibicides primitiva*, *Ehrenbergina mestayeri*, *Cavelinopsis hamatus*, *Siphonaperta macbethi*. Species that occur wherever sediment is relatively coarse on the continental slope include *Dyocibicides* *primitiva*, *Gavelinopsis hamatus*, *Laticarinina altocamerata* and *Planodiscorbis rarescens*.

Thus some generalisations may be made about the environmental preferences of some species in the study area. However, species that are characteristic of a particular depth range in this area are not necessarily characteristic of the same depths everywhere. A limiting environmental factor that varies with depth may be at a completely different depth range elsewhere. For instance, *Stainforthia concava*, noted in this account as being characteristic of the continental slope was first described from cold, shallow waters off Scandinavia. It may be limited more by temperature than any other factor. Hence depth ranges and biofacies described in this account should be used with caution when interpreting environments of deposition of ancient foraminiferal faunas. Further studies of the fauna around New Zealand may show which of many environmental factors control the distribution of the more common species.

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GENERAL CONCLUSIONS

CONCLUSIONS OF LOCAL IMPORTANCE

1. Since Miocene times the seabed has been folding into anticlinal ridges and synclinal depressions paralleling the regional trend on the adjacent land.

2. The zero isobase, separating a rising landward area from a downwarping seaward area, varies in position between the inner and the middle part of the continental shelf and crosses axes of plunging folds.

3. On the coast and continental shelf, rates of tilting range from 2 to 36 microdegrees/thousand years and rates of vertical movement range from +1.7 to -1.5 m/thousand years.

4. At present deposition is most rapid on the inner part of the continental shelf 5-10 km from shore. On any line normal to the shore the maximum rate of deposition is between 1 and 4 m/thousand years, rates being most rapid on the south side of major river mouths. In continental slope depressions sediment-

ation rates range from 0.36 m/thousand years on a relatively nearshore depression to 0.02 m/thousand years in the depression furthest from the shore. On the continental slope ridges rates are too slow to measure.

5. Ash of the Waimihia Formation, erupted about 3.4 thousand years ago can be recognised more than 100 km east of the Hawkes Bay coast.

6. Detrital sediment becomes finer away from the shore but is bimodal because flocs are deposited with discrete grains. On the ridges comparatively little detrital sediment settles and airfall ash, foraminifera and glauconite are important constituents of the sediment. Turbidite layers are common in depressions downslope from channels that incise the continental shelf, a maximum of eight layers having been deposited at one place during the last 3.4 thousand years.

7. Distinctive foraminiferal biofacies characterised different depths and different sediment types.

CONCLUSIONS OF GENERAL APPLICATION

1. Late Quaternary sedimentary and tectonic processes are studied more easily in areas of rapid tectonic movement than in stable areas.

2. The boundary between net erosion and net deposition, which is usually just seaward of the shore, tends to migrate towards the zero isobase, consequently the zero isobase is usually on the inner continental shelf.

3. A zone of wave-planation and a zone of rapid deposition migrated to and fro, in response to Late Quaternary eustatic changes of sea level across the seaward tilting substrate. Surfaces formed by wave-planation during periods of relatively high sea level are preserved on land as raised marine benches. Those formed by wave-planation during low sea level are preserved as unconformities beneath the continental shelf. Successive

positions of the zone of rapid deposition are recorded by discrete prisms of sediment.

4. To seaward of the zero isobase the continental shelf and upper slope is built both upwards and outwards by prisms of sediment. Prisms deposited during periods of high sea level are at their thickest beneath the continental shelf and prisms deposited during periods of low sea level are at their thickest beneath the upper slope.

5. The shelf break was formed, in general, about 20 thousand years ago. Its depth varies according to the degree induration of the sediment that forms it. At places where the shelf break is composed of soft Late Quaternary sediment it is as much as 60 m deeper than at places where it is composed of indurated Tertiary strata. The type of sediment at the shelf break is in turn a complex function of the rates of tectonic processes and rates of deposition of mud.

6. Slumping occurs on slopes as gentle as 1°.