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BULLETIN 171

SEDIMENTATION IN HAWKE BAY

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H. M. PANTIN

New Zealand Oceanographic Institute Memoir No. 28

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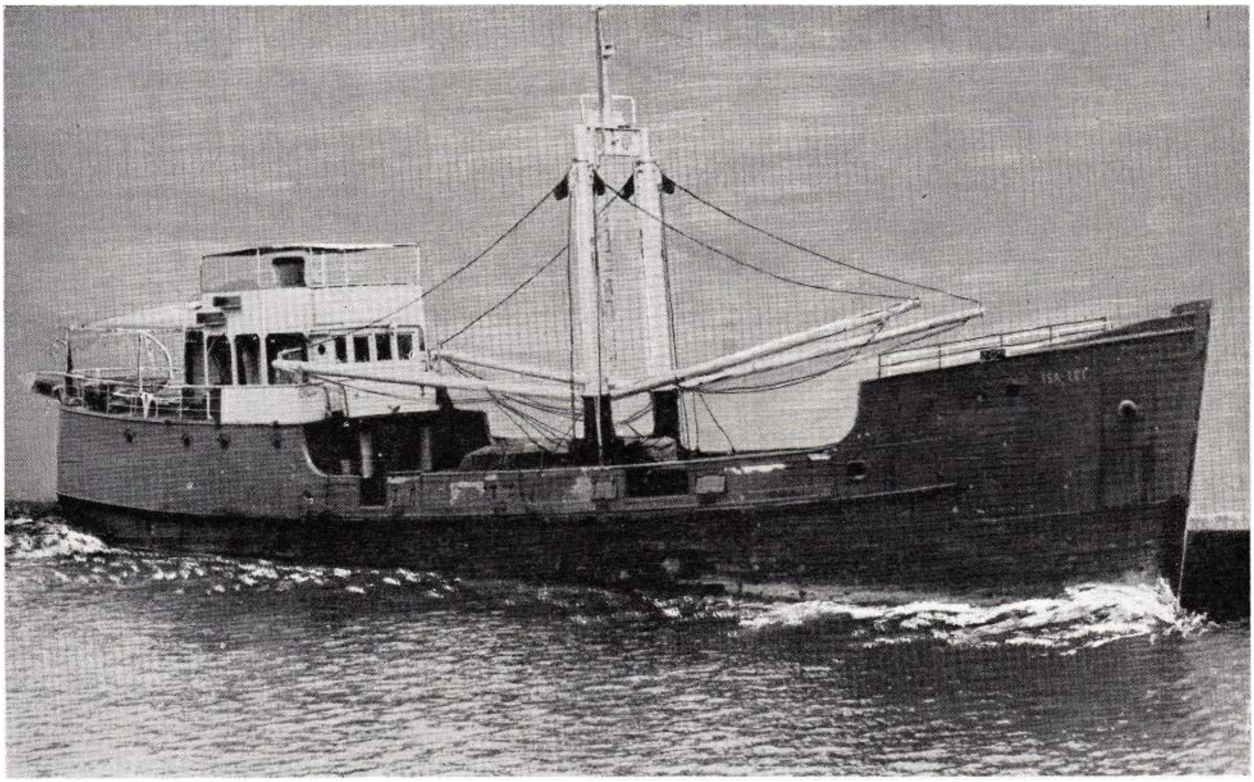

Photograph: *Royal N.Z. Navy*

RNZFA *Isa Lei* from which some of the Hawke Bay sampling was carried out.

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FOREWORD

Until recently, no substantial studies of the distribution of sediments on the New Zealand shelf have been carried out. This memoir presents the results of the first such investigation carried out by the Institute, and considers the nature and origin of the superficial sediment over an area of 1000 square miles of the eastern shelf.

The material has been prepared for publication and received preliminary editing by Mrs P. M. Cullen.

J. W. Brodie, Director,
New Zealand Oceanographic Institute, Wellington.

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PLATES

SEDIMENTATION IN HAWKE BAY

Abstract

The surface sediments in Hawke Bay are divided into five groups: offshore gravel zones, sand belt, mud belt, central zone, and sediments associated with the Lachlan Ridge. These distinctions are made primarily on grain size.

Over much of the Bay a relatively coarse sediment layer, sampled by coring, appears as a subsurface reflector on echo-sounding records. This layer underlies the relatively fine sediments of the mud belt and outcrops in the central zone. Shell material from the central zone has been ^{14}C-dated as approximately 10,000 years B.P. The subsurface reflector shows the effect of faulting.

The sand belt separates the mud belt from the shoreline and the distribution of these two zones appears to be governed by present-day sedimentation.

The central zone and parts of the Lachlan Ridge are at present non-sedimentation areas. Other parts of the Lachlan Ridge are areas of slow sedimentation.

Clastic minerals in the sediments of the Bay are mainly derived from the Mesozoic greywacke suite of the North Island or from the Taupo volcanic sequence, Quaternary in age, which covers a wide area in the region of Lake Taupo and includes ash layers extending as far as the coast of Hawke Bay. Tertiary sedimentary rock fragments are common only on the Lachlan Ridge. Authigenic glauconite is present on the Lachlan Ridge and in part of the sand belt. The mineral occurs as ovoids, subangular grains, pumice vesicle infillings, and foraminiferal infillings.

Yellowish pumice infillings, which occur in the central zone and on parts of the Lachlan Ridge, apparently owe their colour to primary authigenic limonite. Secondary authigenic limonite, formed by the oxidation of glauconite, is found in the same areas as the latter mineral.

TOPOGRAPHICAL AND GEOLOGICAL SETTING

Hawke Bay is a conspicuous re-entrant on the east coast of the North Island, New Zealand, measuring some 50 miles from north-east to south-west and extending about 25 miles inwards from the general line of the coast (Fig. 1). The landscape is mostly rugged and hilly with a deeply incised fluvial topography, the principal exception being the wide, low-lying Heretaunga Plains. The high relief is largely due to rapid uplift during the late Quaternary; the numerous marine benches and river terraces, together with the uplift of the coast in the Napier-Wairoa district at the time of the 1931 earthquake,* show that tectonic activity has continued up to the present day.

Morphologically the coast varies from sectors with high undulating sea cliffs to low-lying sectors with gravel bars and sandhills. The sea cliffs have been cut by marine erosion across spurs and ridges of soft Tertiary or Lower Quaternary rocks. Cliffs ranging from 200 ft to 500 ft in height run from Cape Kidnappers to Clifton. Between Tangoio Bluff and Matangimomoe a long line of cliffs rises from 200 ft in the south to nearly 1300 ft in the north. The height of the cliffs then decreases rapidly, falling to 400–500 ft about 2½ miles north-east of Matangimomoe. Cliffs up to 600 ft in height are present along much of the coast between Matangimomoe and Tuhara, although the cliff-line is more broken by stream and river valleys than is the case between Tangoio Bluff and Matangimomoe. Cliffs up to 200 ft in height occur locally around Waikokopu. Cliffs are again present along many parts of Mahia Peninsula, and range up to 600 ft in height, although they are usually only 200–400 ft high. Portland Island is ringed by steep bluffs and cliffs 200–300 ft high. (Fig. 2.)

The low-lying parts of the coast are late Quaternary aggradation surfaces, the deposits consisting of sands and gravels in various proportions. The most extensive of these low-lying sectors runs from Clifton to Tangoio Bluff, with Napier in the centre. The coast in this sector corresponds to the seaward margin of the Here-

* The maximum coastal uplift associated with the 1931 earthquake was 9 ft (Marshall, 1933, pp. 81, 86).

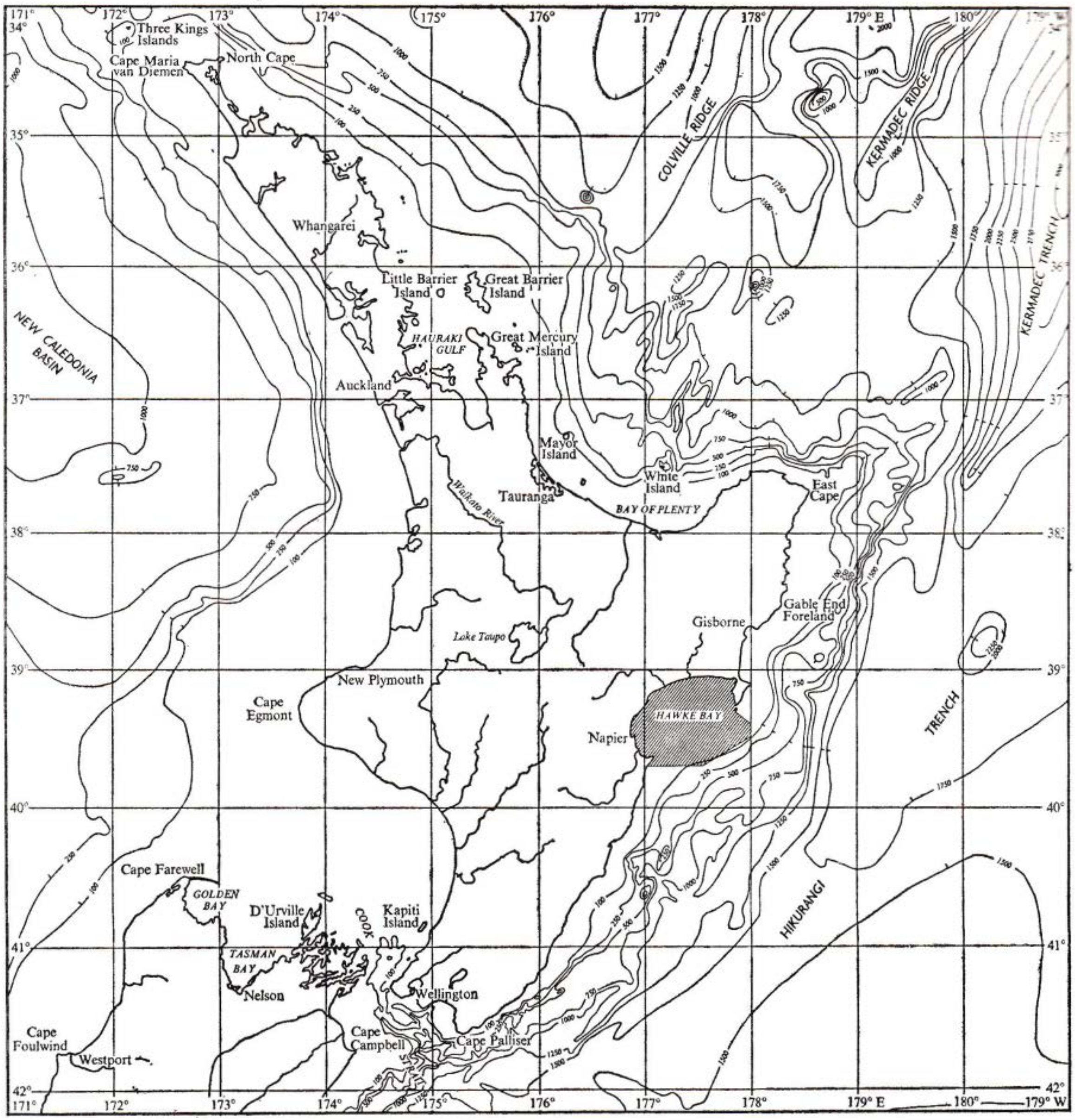


FIG. 1. Locality map. (Depths in fathoms.)

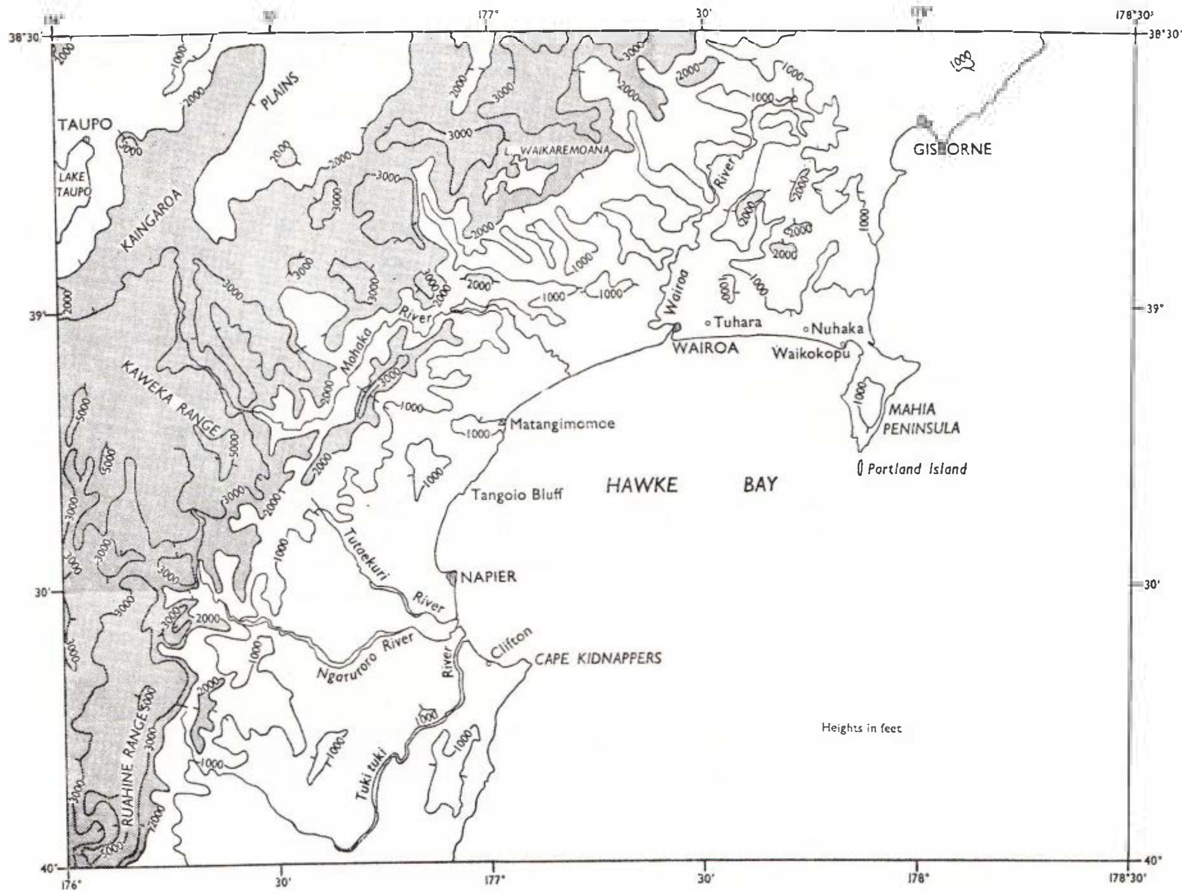


FIG. 2. Topographic map of the Hawke's Bay coastal area from Lands and Survey Department map NZMS 19 Sheet 3.

taunga Plains, the only interruption in the general low relief being the 335 ft bluff around which the town of Napier is built. The bluff is mainly of Lower Quaternary limestone. Until the 1931 earthquake it was partly isolated from the mainland by marshes, and this gave rise to the name still in use, Scinde Island. Both fluvial and marine deposition have played a part in the formation of the Heretaunga Plains.

In the northern part of the bay, between Tuhara and Nuhaka, the coastal hills are fronted by a low-lying belt up to 2 miles in width, with sandhills and lagoons. Here also, fluvial and marine processes have both been active, although the effects of wind action are more conspicuous than in the Heretaunga Plains. Another low-lying sector with sandhills and small lagoons is the narrow tombolo, formed by marine aggradation and modified by wind action, connecting Mahia Peninsula with the mainland.

Marine benches are conspicuous along some parts of the coast. In the Cape Kidnappers area, the hills are capped by a series of uplifted marine benches 700–900 ft above sea level. Between Tangoio Bluff and Matangimomoe, some of the hills are capped by a well developed surface extending several miles inland from the top of the coastal cliffs. This surface is probably a plain of marine erosion, dissected by fluvial action and warped by tectonic movements. Well developed benches on the southern and eastern extremities of Mahia Peninsula are approximately 350 ft and 450 ft high respectively. Portland Island, which is tabular in shape, is capped by a well developed bench at a height varying from 300 ft in the north-east to 200 ft in the south-west.

The five main rivers draining into Hawke Bay are listed below, with estimates of the relative rates of discharge obtained by multiplying the catchment area of each river by the approximate annual rainfall over the catchment. The values are as follows:

Table 1. Rates of Discharge of Hawke's Bay Rivers

River	Catchment Area* (sq. miles)	Approximate Rainfall† (inches/year)	Product
Tukituki	955	40	38,200
Ngaruroro	970	35	33,950
Tutaekuri	345	40	13,800
Mohaka	915	60	54,900
Wairoa	1,410	70	98,700

* Data taken from Cowie, 1957, Fig. 29.
† Estimated from data given in Garnier, 1958, Fig. 7.

Assuming that evaporation and transpiration losses do not differ greatly from one catchment to another in the Hawke's Bay area, these figures show that the flow of fresh water into the Bay from the two more northerly rivers (Wairoa and Mohaka) is somewhat greater than the combined inflow from the southern group of rivers (Tukituki, Ngaruroro, and Tutaekuri). The three southern rivers emerge from valleys in the hills and flow the last few miles to the sea over the low-lying ground south of Napier. The Mohaka River, however, flows in a deep valley that continues right up to the coast, and high sea cliffs lie on either side of the river mouth. The Wairoa River emerges from hilly country about a mile from the coast, and flows to the sea across a low alluvial terrace flanked by sea cliffs on either side.

The sedimentary rocks and sediments around Hawke Bay range in age from Miocene (Taranaki Series) to present day (Fig. 3). The Miocene beds consist mainly of massive calcareous siltstones and sequences of alternating sandstone and muddy siltstone. The Pliocene and Pleistocene beds include sands, silts, limestones, and conglomerates; the limestones are frequently recrystallised, but the rest are only semi-consolidated. The Holocene deposits are unconsolidated marine sands and gravels interbedded with fluvial sands, gravels, and silts.

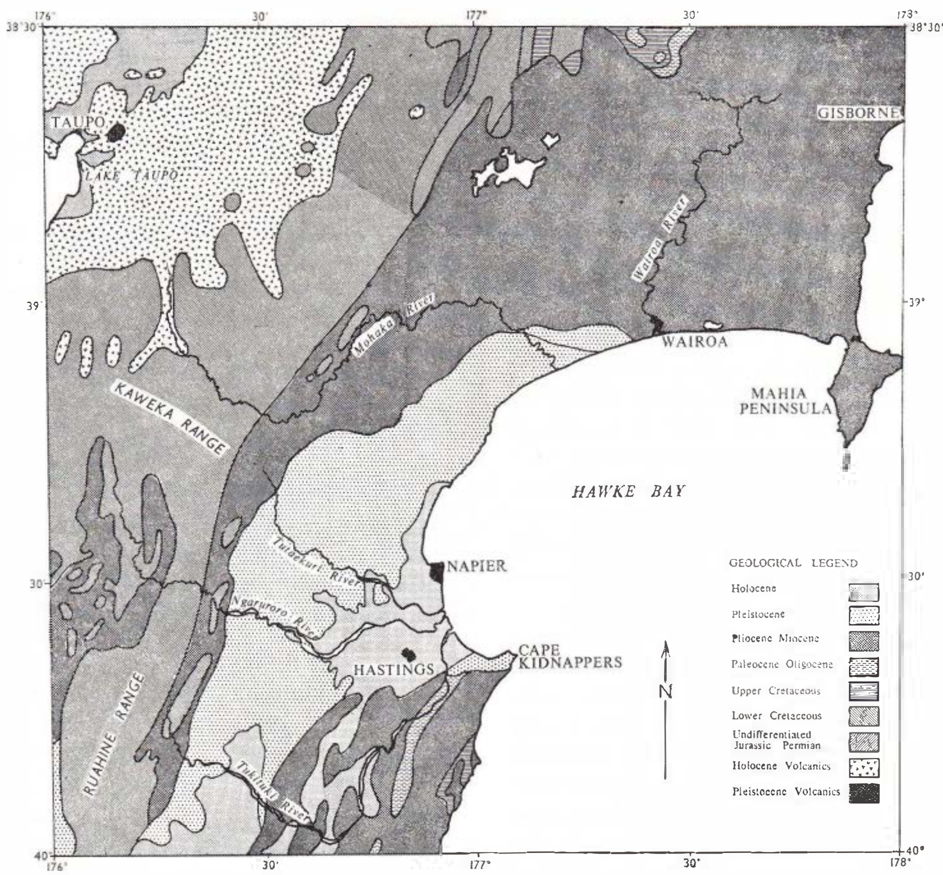


Fig. 3. Geology of the coastal areas of Hawke's Bay (from the N.Z. Geological Survey, Geological Map of New Zealand 1:2,000,000, 1958).

Folding and faulting are widespread in the country rocks of northern Hawke's Bay Province. Movements have continued at intervals throughout most of the Tertiary up to the present day, but the two main pulses took place during the late Oligocene and the Lower Pleistocene. The most conspicuous folding is in the areas of Tertiary rocks, that is between Portland Island and Wairoa, and around Cape Kidnappers. The folds trend consistently about 30° E of N and are usually open, with dips on the limbs ranging up to about 20°, although steeper dips are found locally. The Quaternary rocks on the west side of the Bay occupy a wide structural depression trending approximately NE-SW, with dips reaching 10° on the flanks. In all formations, there is a general tendency for beds to dip towards the centre of the Bay. The dominant trend of the faults is also about 30° E of N. Faults with this trend show dextral transcurrent displacement as well as normal or reversed faulting.

This brief geological summary has been compiled with the aid of the following New Zealand Geological Survey maps:

Geological Map of New Zealand. Sheet 8 – Taupo. 1:250,000. 1960.

Geological Map of New Zealand. Sheet 11 – Dannevirke. 1:250,000. 1962.

Geological Map, New Zealand. North Island. 1:1,013760. 1947.

Aspects of the tectonic history of Hawke Bay are covered by Pantin (1963) in sections dealing with the morphology of the continental shelf between Cape Palliser and Gable End Foreland (probable zones of uplift and subsidence in the Hawke Bay region are shown in Pantin, *loc. cit.*, Fig. 10).

BATHYMETRY

Sources of Data

The first bathymetric survey of Hawke Bay was carried out during the years 1849–55 by HMS *Acheron* and HMS *Pandora,* using the hand-line method, and the results of this survey appear on the older charts as a series of spot soundings. In 1953–7, the bathymetry of the bay was thoroughly revised as part of an echo-sounding survey programme organised by the New Zealand Naval Hydrographic Branch and covering the east coast of the North Island from Cape Palliser to Gable End Foreland. The survey was carried out by the survey frigate HMNZS *Lachlan,* accompanied by the motor launches Takapu and Tarapunga. The frigate surveyed the deeper parts of the bay, and the two motor-launches covered the shallower inshore areas. Echo-sounding traverses were spaced at intervals of ½ to 1 mile, the narrower intervals being in the shallower parts of the bay. The positions of the traverses were

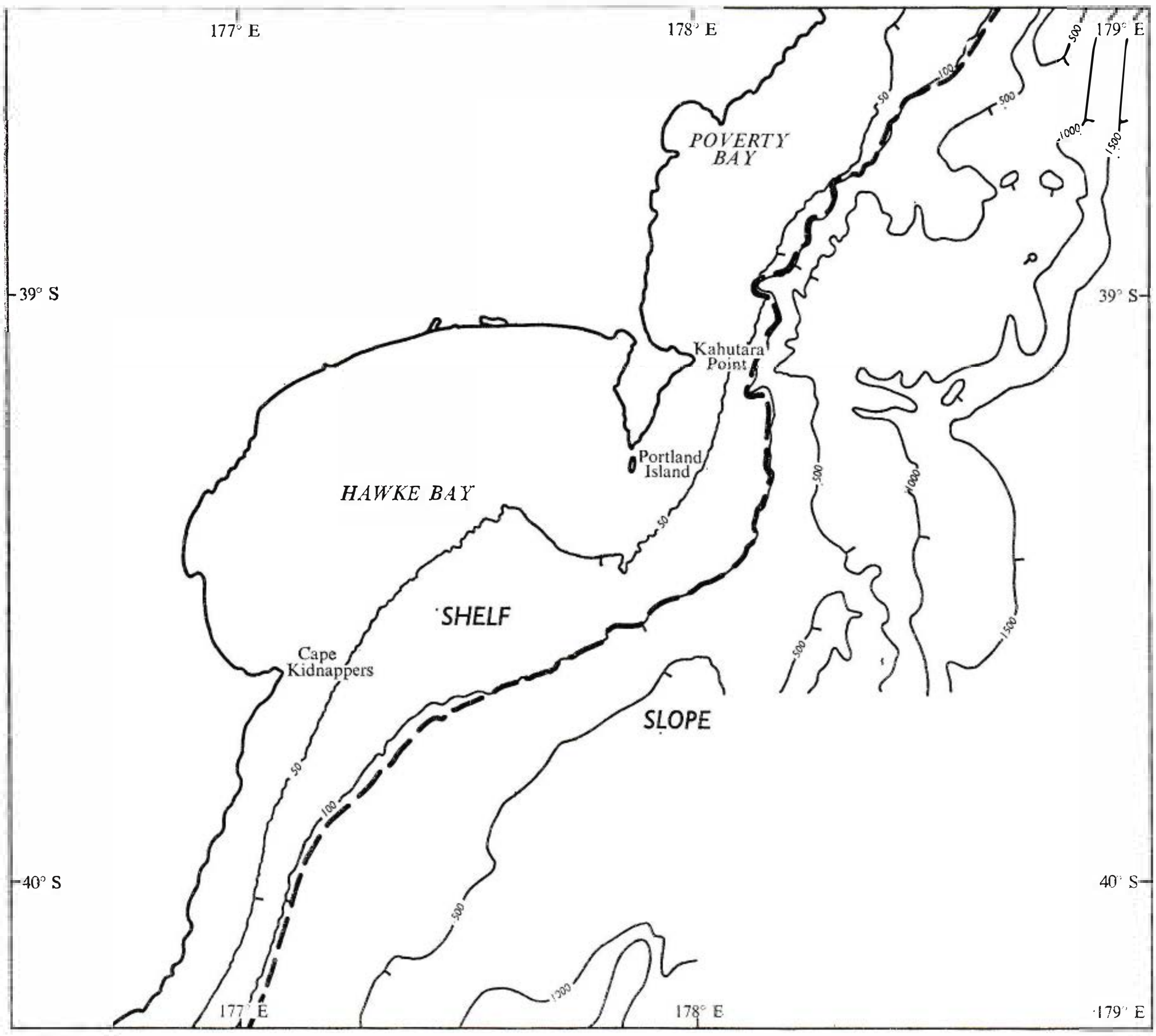


Fig. 4. Outline of bathymetry with position of shelf, slope, and shelf edge (heavy broken line) in Hawke Bay. Depths in fathoms.

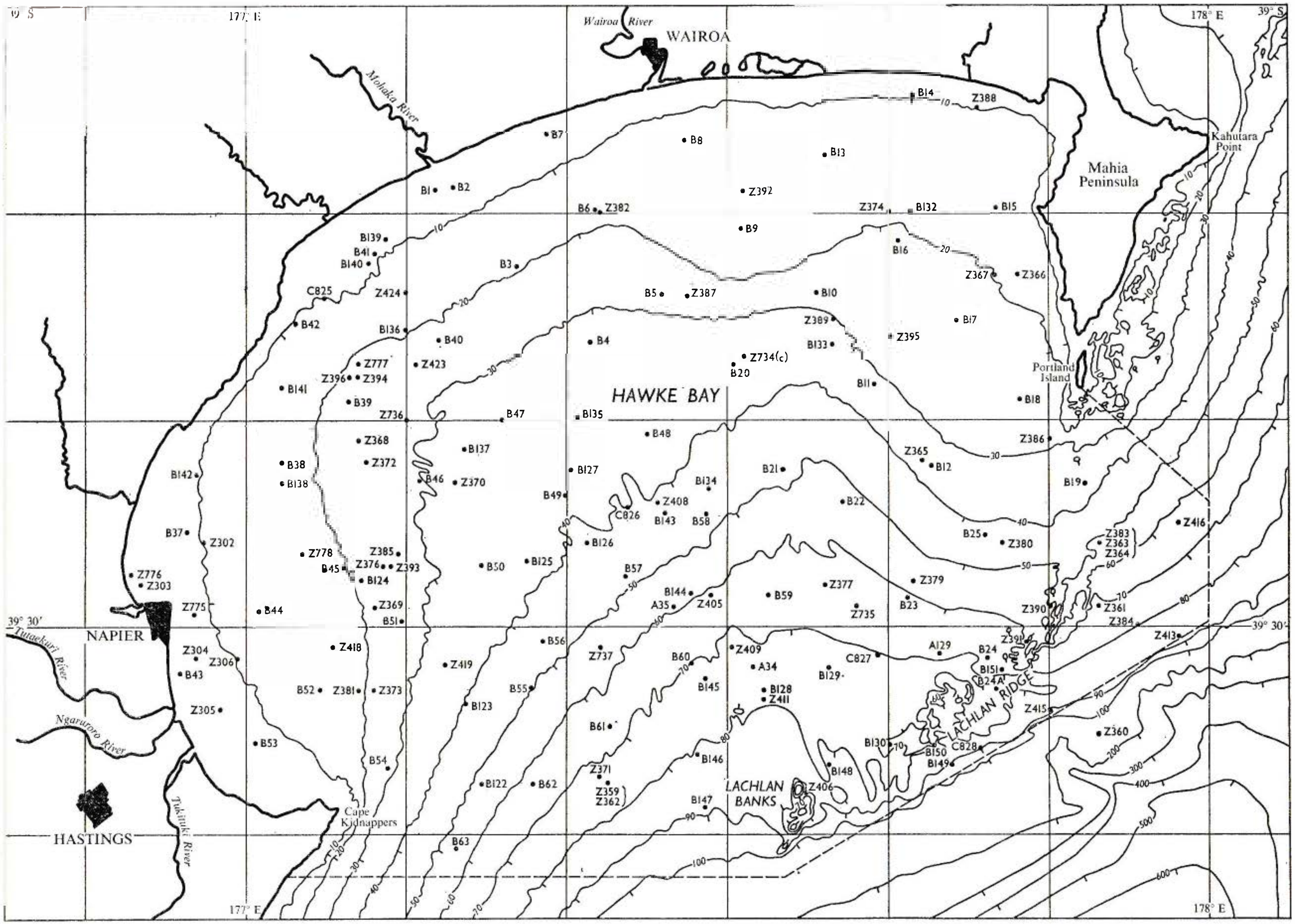


FIG. 5. Detailed bathymetry (Pantin, 1963) and station positions, Hawke Bay. Depths in fathoms. Seaward limits of described area indicated by broken line.

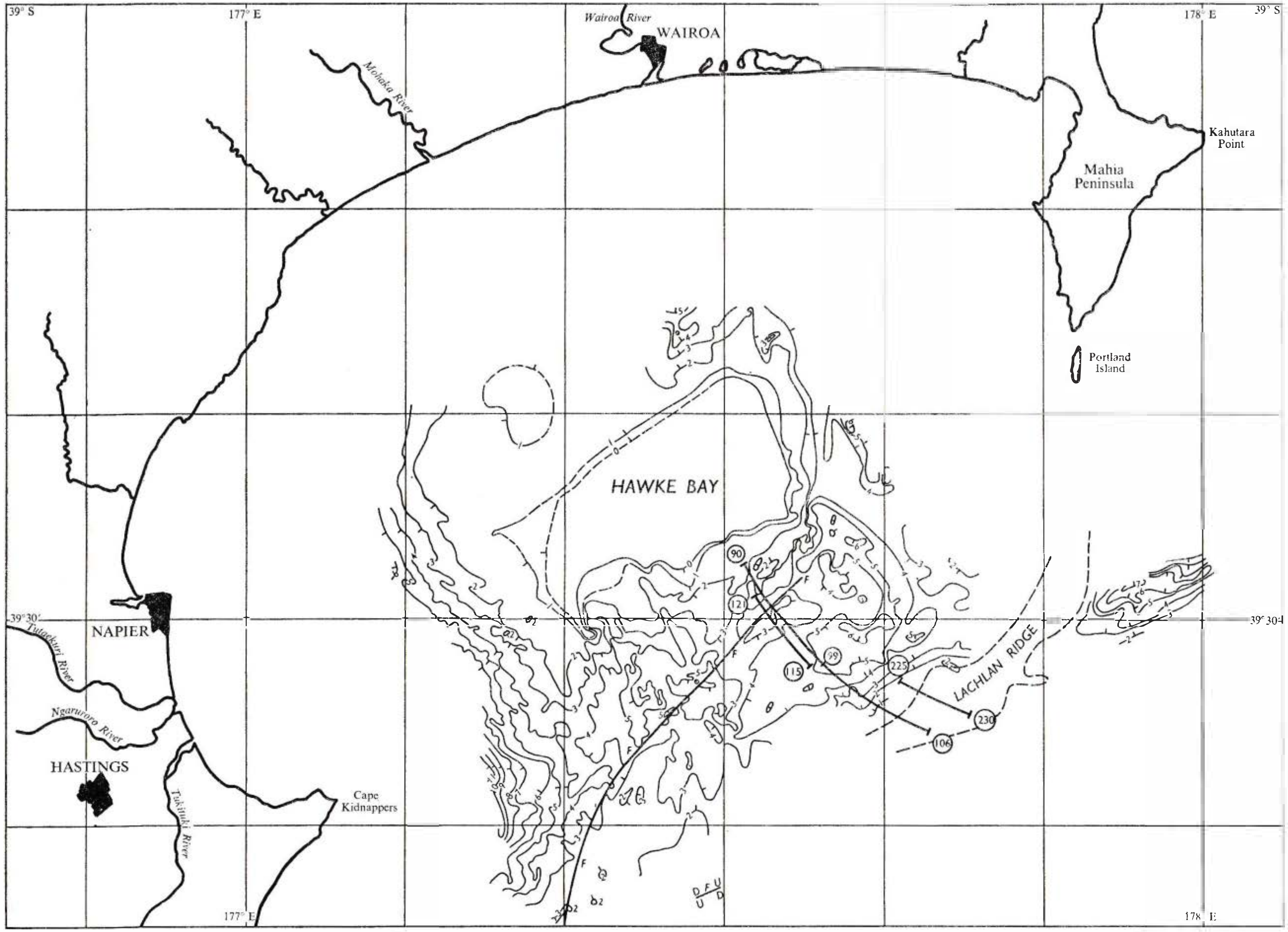


FIG. 6. Isopachs on main subsurface reflector within the sediments. Intervals in fathoms. The positions of echo-sounding lines (Plate 4) are given by the fix numbers, 225-230, 90-99, 99-106, and 121-115. The Kidnappers Fault and a small subsidiary fault are also shown.
|———| = echo-sounding lines ——— F = fault; D = downthrow; U = upthrow.

plotted on track charts, and collector charts were made by plotting the echo-sounding data on the appropriate tracks. Depths were measured at close and fairly regular intervals on the actual sounding records (the intervals being in most cases only ¼ to ½ mile) and then plotted as numerals on the collector charts. Copies of the collector charts were forwarded to the New Zealand Oceanographic Institute by the Hydrographic Branch, and the bathymetric contours were drawn by members of the Institute.

Description of Bathymetry

The whole of Hawke Bay lies within the continental shelf (Fig. 4). Over most of the bay, the sea bed is virtually smooth, with isobaths conforming in shape to the general outline of the coast, and gradients varying from 1:150 to 1:700. Many of the minor irregularities in the isobaths tend to run parallel to the sounding lines, and must often be due to small errors in depth or position, although some of these irregularities may be genuine. In contrast to the dominantly smooth bathymetry, there are a few localised areas with conspicuously irregular topography. A number of small banks lie around Portland Island, mostly within the 20-fathom isobath and rising 5–10 fathoms above the general level of the surrounding sea bed. The most extensive zone of irregular topography is the Lachlan Ridge, which runs south-westwards from a point about 8 miles south of Portland Island. The ridge is 2–4 miles wide and 13 miles long, with a relief of 15 fathoms. The general level on either side of the ridge varies from 50 fathoms in the north-east to 80 fathoms in the south-west. Six miles south-west of the ridge the Lachlan Banks rise abruptly from 80 fathoms, reaching a minimum depth of 50 fathoms at the summit of the most northerly bank. (Fig. 5.)

The general line of the shelf margin opposite Hawke Bay swings outwards to some extent, causing the shelf in the Hawke Bay sector to be much wider than in adjacent areas to north and south. The maximum width of the shelf opposite the centre of the bay is thus about 37 miles, as opposed to 14 miles opposite Cape Kidnappers and 14 miles opposite Portland Island. The depth

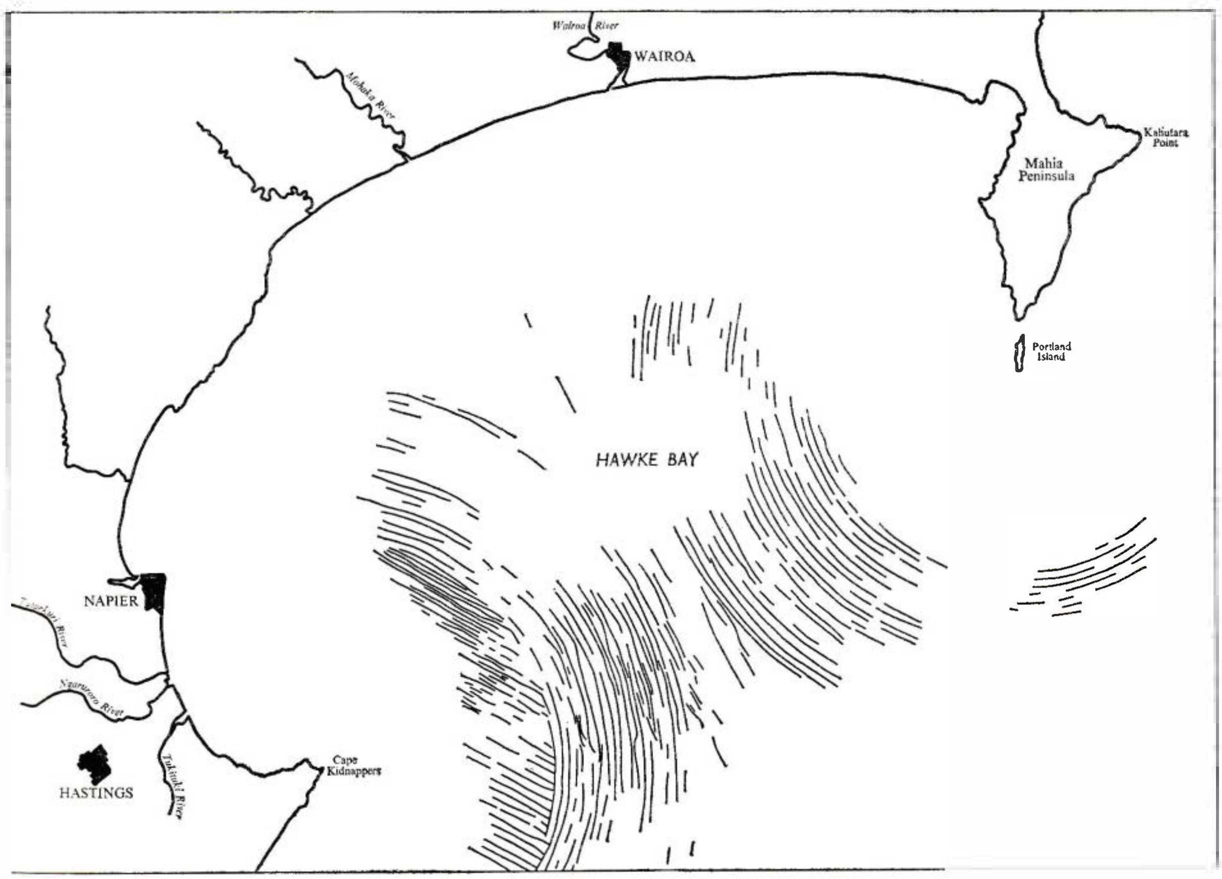


Fig. 7. Distribution of sounding lines that show subsurface reflecting horizons.

of the shelf edge outside the bay varies to some extent, falling from 90 fathoms east of Mahia Peninsula to 110 fathoms opposite the southern part of the bay.

The echo-sounding records reveal distinct reflections from surfaces below the sea bed over a wide area in the central part of the Bay. (Figs. 6, 7; Plate 4.) The depth of the main reflector below the sea bed is usually 3–6 fathoms, but this increases in places to as much as 11 fathoms, and decreases to nil in a zone $6\frac{1}{2}$ by 13 miles in the centre of the Bay. One or two additional reflectors are occasionally visible between the main reflector and the sea bed. These sub-surface reflectors are undoubtedly due to sedimentary discontinuities, as has been proved by bottom sampling.

The soundings also show a fault (which must have been active within very recent times) in the outer part of the Bay, about 7 miles north-west of the Lachlan Banks. This fault is here named the Kidnappers Fault. It is visible as a small vertical displacement of the main sub-surface reflector, and frequently as a small scarp on the sea bed. The fault runs NE-SW for about 20 miles, with a slight curvature to the north-west, and the down-throw is consistently to the north-west, with a vertical displacement ranging up to 4 fathoms. There is also a small fault about 6 miles south-west of the Lachlan Banks, with an ENE-WSW trend. The vertical displacement of this fault is small and reverses along its length, the north-west side being downthrown at one end and the south-east side at the other.

Sediment Sampling

A total of 151 sediment samples were collected during this study (see Table 2). Most were obtained on three N.Z. Oceanographic Institute cruises on RNZFA *Tui* 1956, FRV *Ikatere* 1957, RNZFA *Isa Lei* 1957. Other samples were taken by HMNZS *Lachlan* during the course of charting operations 1953–7, and some were collected during the *Kotuku* expedition 1952 and kindly made available by Dr J. C. Yaldwyn. Some final sampling was carried out from MV *Taranui* 1962. The bulk of the samples were collected by cone dredge and a lesser number by Dietz grab. The *Lachlan* samples were collected principally by Worzel sampler. A total of 26 2 in. diameter piston cores of significant length were collected, most being from *Isa Lei* and the rest from *Tui*.

The surface samples and selected portions of core samples were subjected to mechanical analysis. Grain counts were made on sand fractions, and significant detrital components were examined petrographically.

All cores of significant length were examined and logged (Fig. 8)*; their general characteristics are as follows (symbols SB, MT, etc., are marked and explained on Fig. 8).

B 21

The major part consists of muddy sand containing numerous shells and shell fragments, but virtually no pebbles. This is overlain by very muddy sand containing numerous pebbles in addition to shell fragments.

B 22

Slightly sandy mud. Pumice is the main component in the coarse sand fraction, while mineral grains predominate in the fine sand fraction. Near the top of the core is a sharply defined band (marked SB) with a higher proportion of sand than the sediment above and below. Faint lamination is present in the lower part of the band, but this feature is not found above MT, where the proportion of mud increases.

B 23

The upper, major portion was severely disturbed during extrusion, and was rejected. The total length shown is the wet length of the core.

B 24A

Sandy mud. Pumice is the most abundant constituent in the coarse sand fraction, but shell fragments are also very numerous. Mineral grains are dominant in the fine sand fraction. The highest proportion of coarse sand occurs between CT and (C)T. The largest pumice fragments (up to 3 mm in diameter) and shell fragments (up to 7 mm) are also found in this zone.

B 122

Slightly sandy mud. Mineral grains are the dominant constituent of the sand fraction, but pumice is also present. The proportion of pumice increases abruptly at VT, but decreases progressively from there towards the top of the core.

B 123

Sandy mud. Pumice is the dominant constituent of the sand fraction. The proportion of pumice increases abruptly at VT. This increase is partly compensated by a decrease at (V)T, but there is a further progressive decrease in pumice content from (V)T to the top of the core.

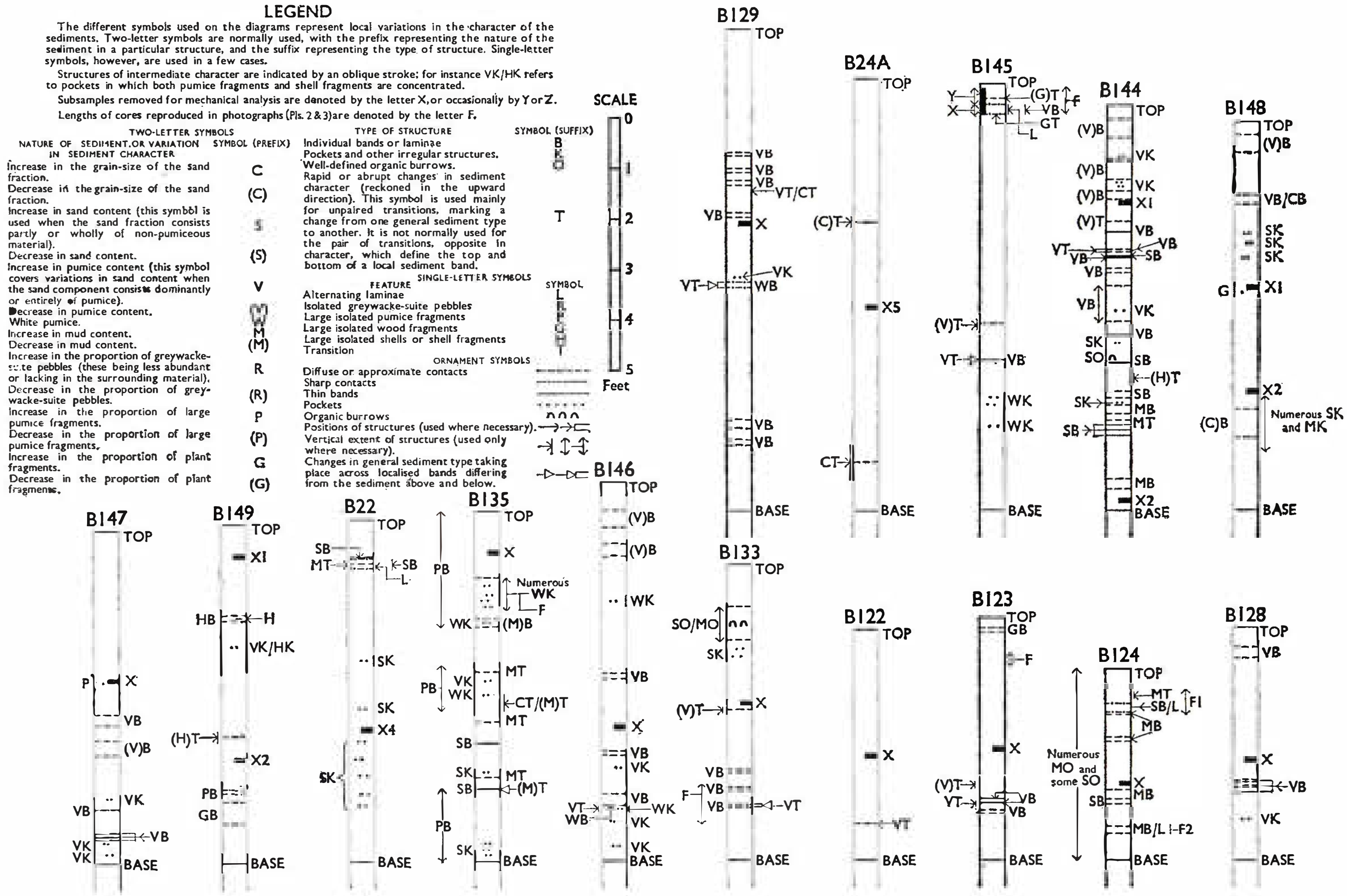
* Dry lengths of cores are given unless otherwise stated.

Table 2. Station List

N.Z.O.I. Station No.	Latitude S	Longitude E	Depth (fm)
A 34	39° 32·0′	177° 31·6′	74
A 35	39° 29·0′	177° 26·6′	58
A 129	39° 31·4′	177° 43·2′	68
B 1	39° 08·8′	177° 11·8′	6
B 2	39° 08·8′	177° 13·0′	7
B 3	39° 12·7′	177° 17·0′	19
B 4	39° 16·3′	177° 21·4′	33
B 5	39° 13·9′	177° 25·9′	23
B 6	39° 09·9′	177° 21·7′	18
B 7	39° 06·2′	177° 18·7′	6
B 8	39° 06·6′	177° 27·3′	13
B 9	39° 10·9′	177° 30·8′	16
B 10	39° 13·9′	177° 35·4′	28
B 11	39° 18·4′	177° 39·0′	34
B 12	39° 22·2′	177° 42·5′	37
B 13	39° 07·4′	177° 36·0′	14
B 14	39° 04·4′	177° 41·5′	9
B 15	39° 09·8′	177° 46·6′	17
B 16	39° 11·3′	177° 40·6′	20
B 17	39° 15·3′	177° 44·2′	22
B 18	39° 19·0′	177° 48·2′	23
B 19	39° 23·0′	177° 52·0′	37
B 20	39° 17·5′	177° 30·4′	37
B 21	39° 22·4′	177° 33·4′	48
B 22	39° 23·9′	177° 37·0′	55
B 23	39° 28·6′	177° 41·2′	60
B 24	39° 31·6′	177° 46·0′	68
B 24A	39° 33·1′	177° 46·6′	76
B 25	39° 25·6′	177° 45·9′	43
B 37	39° 25·4′	176° 56·2′	9
B 38	39° 22·0′	177° 02·3′	16
B 39	39° 19·1′	177° 06·4′	22
B 40	39° 16·2′	177° 11·9′	23
B 41	39° 12·0′	177° 08·1′	9
B 42	39° 15·4′	177° 03·0′	11
B 43	39° 32·2′	176° 55·8′	5
B 44	39° 29·3′	177° 00·8′	12
B 45	39° 27·1′	177° 06·2′	19
B 46	39° 23·0′	177° 10·8′	29
B 47	39° 20·0′	177° 16·0′	34
B 48	39° 20·8′	177° 25·0′	37
B 49	39° 23·8′	177° 19·8′	37
B 50	39° 27·1′	177° 14·6′	34
B 51	39° 29·8′	177° 09·7′	25
B 52	39° 33·1′	177° 04·6′	14
B 53	39° 35·6′	177° 00·6′	7
B 54	39° 36·8′	177° 08·7′	28
B 55	39° 33·8′	177° 13·6′	40
B 56	39° 30·8′	177° 18·4′	46
B 57	39° 27·7′	177° 23·5′	48
B 58	39° 24·5′	177° 28·6′	47
B 59	39° 28·5′	177° 32·5′	66
B 60	39° 31·9′	177° 27·6′	70
B 61	39° 34·8′	177° 22·7′	66
B 62	39° 37·5′	177° 17·8′	63
B 63	39° 40·7′	177° 13·0′	54
B 122	39° 37·5′	177° 14·6′	51
B 123	39° 32·9′	177° 17·7′	49
B 124	39° 27·7′	177° 07·3′	21
B 125	39° 26·9′	177° 17·5′	37
B 126	39° 26·0′	177° 21·2′	42
B 127	39° 22·4′	177° 20·2′	38
B 128	39° 33·2′	177° 32·2′	77
B 129	39° 32·1′	177° 36·2′	74
B 130	39° 35·8′	177° 40·0′	67
B 131	39° 36·6′	177° 43·8′	90
B 132A	39° 10·0′	177° 41·3′	19
B 132B	39° 10·0′	177° 41·3′	19
B 133	39° 16·5′	177° 36·4′	33
B 134	39° 23·4′	177° 28·8′	46
B 135	39° 19·9′	177° 20·4′	36
B 136	39° 15·7′	177° 10·0′	19
B 137	39° 21·4′	177° 13·6′	31
B 138	39° 23·1′	177° 02·2′	16
B 139	39° 11·4′	177° 08·6′	9
B 140	39° 12·4′	177° 07·6′	9

Table 2—*continued*

N.Z.O.I. Station No.	Latitude S	Longitude E	Depth (fm)
B 141	39° 18·5′	177° 02·2′	14
B 142	39° 22·6′	176° 56·9′	9
B 143	39° 24·6′	177° 26·0′	42
B 144	39° 28·5′	177° 27·5′	58
B 145	39° 32·5′	177° 28·5′	73
B 146	39° 36·2′	177° 28·0′	82
B 147	39° 38·7′	177° 28·5′	89
B 148	39° 36·6′	177° 36·2′	81
B 149	39° 36·6′	177° 43·8′	90
B 150	39° 35·7′	177° 42·8′	70
B 151	39° 32·1′	177° 46·9′	63
C 825	39° 14·0′	177° 05·0′	10
C 826	39° 24·2′	177° 23·8′	40
C 827	39° 31·4′	177° 39·4′	70
C 828	39° 36·1′	177° 45·6′	91
Z 302	39° 26·1′	176° 57·4′	10
Z 303	39° 28·0′	176° 53·4′	3
Z 304	39° 31·4′	176° 56·8′	7
Z 305	39° 34·0′	176° 58·4′	7
Z 306	39° 31·6′	176° 59·3′	9
Z 359	39° 37·5′	177° 22·5′	75
Z 361	39° 29·0′	177° 53·0′	71
Z 362	39° 37·5′	177° 22·5′	75
Z 363	39° 26·0′	177° 53·0′	54
Z 364	39° 26·0′	177° 53·0′	54
Z 365	39° 22·0′	177° 42·0′	38
Z 366	39° 13·0′	177° 48·0′	19
Z 367	39° 13·0′	177° 46·5′	20
Z 368	39° 21·0′	177° 07·1′	25
Z 369	39° 29·0′	177° 08·0′	22
Z 370	39° 23·0′	177° 12·9′	31
Z 371	39° 37·3′	177° 22·0′	73
Z 372	39° 22·0′	177° 07·4′	26
Z 373	39° 33·1′	177° 08·0′	22
Z 374	39° 10·0′	177° 40·0′	19
Z 376	39° 27·2′	177° 08·5′	24
Z 377	39° 28·1′	177° 36·0′	62
Z 379	39° 27·9′	177° 41·6′	58
Z 380	39° 26·0′	177° 47·0′	44
Z 381	39° 33·0′	177° 07·1′	19
Z 382	39° 10·0′	177° 22·1′	18
Z 383	39° 26·0′	177° 53·0′	54
Z 384	39° 30·0′	177° 55·0′	79
Z 385	39° 26·5′	177° 09·4′	27
Z 386	39° 21·0′	177° 50·0′	28
Z 387	39° 14·1′	177° 27·5′	26
Z 388	39° 05·0′	177° 45·6′	10
Z 389	39° 15·3′	177° 36·5′	30
Z 390	39° 29·0′	177° 50·0′	52
Z 391	39° 30·9′	177° 48·6′	58
Z 392	39° 09·0′	177° 31·1′	14
Z 393	39° 27·2′	177° 09·0′	26
Z 394	39° 18·0′	177° 07·0′	23
Z 395	39° 16·1′	177° 40·0′	25
Z 396	39° 18·0′	177° 06·5′	21
Z 405	39° 28·5′	177° 28·9′	60
Z 406	39° 38·0′	177° 34·7′	74
Z 408	39° 24·0′	177° 25·6′	40
Z 409	39° 31·0′	177° 30·2′	73
Z 411	39° 33·5′	177° 32·2′	79
Z 413	39° 30·5′	177° 58·0′	88
Z 415	39° 34·0′	177° 50·0′	88
Z 416	39° 25·0′	177° 57·9′	62
Z 418	39° 31·0′	177° 05·6′	16
Z 419	39° 31·9′	177° 12·4′	34
Z 423	39° 17·4′	177° 10·6′	25
Z 424	39° 13·9′	177° 10·0′	13
Z 734	39° 17·0′	177° 31·1′	37
Z 735	39° 29·0′	177° 38·0′	64
Z 736	39° 20·0′	177° 10·0′	28
Z 737	39° 31·1′	177° 22·1′	55
Z 775	39° 29·4′	176° 56·8′	8
Z 776	39° 27·5′	176° 52·8′	2
Z 777	39° 17·3′	177° 01·0′	21
Z 778	39° 26·5′	177° 03·4′	16


LEGEND
The different symbols used on the diagrams represent local variations in the character of the sediments. Two-letter symbols are normally used, with the prefix representing the nature of the sediment in a particular structure, and the suffix representing the type of structure. Single-letter symbols, however, are used in a few cases.
Structures of intermediate character are indicated by an oblique stroke: for instance VK/HK refers to pockets in which both pumice fragments and shell fragments are concentrated.
Subsamples removed for mechanical analysis are denoted by the letter X, or occasionally by Y or Z.
Lengths of cores reproduced in photographs (Pls. 2 & 3) are denoted by the letter F.
TWO-LETTER SYMBOLS
NATURE OF SEDIMENT, OR VARIATION IN SEDIMENT CHARACTER
SYMBOL (PREFIX)
Increase in the grain-size of the sand fraction. C
Decrease in the grain-size of the sand fraction. (C)
Increase in sand content (this symbol is used when the sand fraction consists partly or wholly of non-pumiceous material). S
Decrease in sand content. (S)
Increase in pumice content (this symbol covers variations in sand content when the sand component consists dominantly or entirely of pumice). V
Decrease in pumice content. (V)
White pumice. W
Increase in mud content. M
Decrease in mud content. (M)
Increase in the proportion of greywacke-suite pebbles (these being less abundant or lacking in the surrounding material). R
Decrease in the proportion of greywacke-suite pebbles. (R)
Increase in the proportion of large pumice fragments. P
Decrease in the proportion of large pumice fragments. (P)
Increase in the proportion of plant fragments. G
Decrease in the proportion of plant fragments. (G)
TYPE OF STRUCTURE
SYMBOL (SUFFIX)
Individual bands or laminae B
Pockets and other irregular structures. K
Well-defined organic burrows. O
Rapid or abrupt changes in sediment character (reckoned in the upward direction). This symbol is used mainly for unpaired transitions, marking a change from one general sediment type to another. It is not normally used for the pair of transitions, opposite in character, which define the top and bottom of a local sediment band. T
SINGLE-LETTER SYMBOLS
FEATURE
SYMBOL
Alternating laminae L
Isolated greywacke-suite pebbles E
Large isolated pumice fragments H
Large isolated wood fragments D
Large isolated shells or shell fragments Q
Transition I
ORNAMENT SYMBOLS
Diffuse or approximate contacts
Sharp contacts
Thin bands
Pockets
Organic burrows
Positions of structures (used where necessary).
Vertical extent of structures (used only where necessary).
Changes in general sediment type taking place across localised bands differing from the sediment above and below.
SCALE
0 1 2 3 4 5
Feet

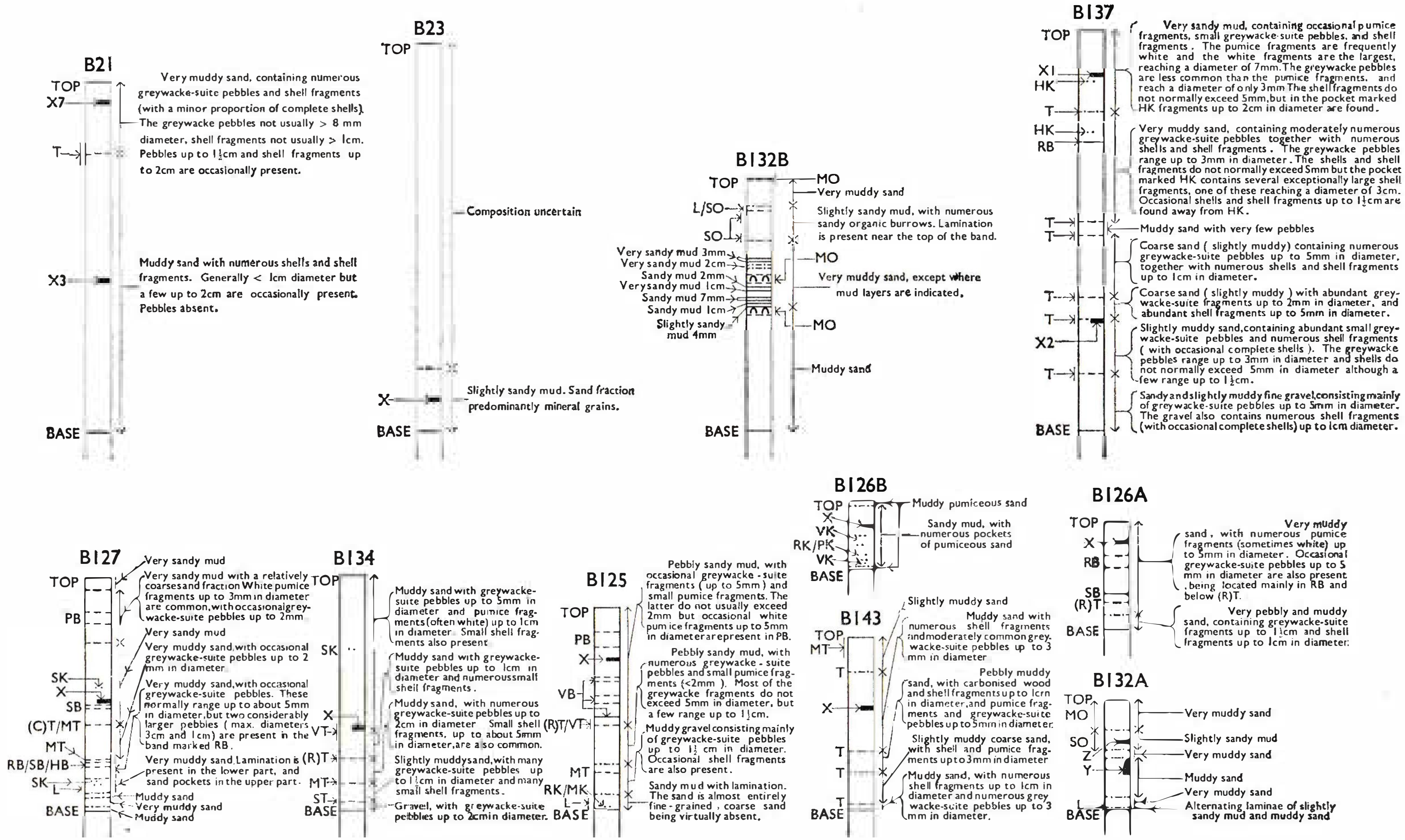


FIG. 8. Stratigraphy of Hawke Bay cores. Dry lengths of cores are shown except for B 23.

B 124

Sandy mud, with numerous muddy organic burrows and a smaller proportion of sandy burrows. Traces of lamination are visible in many places, and this feature is conspicuous in the two bands marked L. Mineral grains are the dominant constituent of the sand fraction.

B 125

Consists principally of bands containing pebbles, sand, and mud in various proportions. Laminated muddy sand occurs near the base. Pumice is the main constituent in the coarse sand fraction, while mineral grains are dominant in the fine sand fraction.

B 126A

Pebbles, mud, and sand in varying proportions. Pumice is the most abundant constituent in the coarse sand fraction, whereas mineral grains are dominant in the fine sand fraction.

B 126B

A layer of sandy mud is overlain and underlain by muddy sand. The sand fraction in the muddy sand is relatively coarse and consists mainly of pumice, while the sand fraction in the sandy mud is relatively fine-grained and consists mainly of mineral grains. The sandy mud possesses a higher silt:clay ratio than most other sediments in the area.

B 127

This core shows a general upward decrease in grain-size, although there are numerous fluctuations in the relative proportions of sand and mud. Mineral grains predominate in the fine sand fraction, while pumice predominates in the coarser sand fraction. The pebble fraction consists mainly of greywacke-suite and shell fragments in the lower part of the core, and pumice in the upper part.

B 128

Slightly sandy mud. Pumice is the dominant constituent in the sand fraction. There is a general decrease in pumice content from the base to the top of the core. Occasional grains of white pumice are present in the lower part of the core.

B 129

Slightly sandy mud. Pumice is the dominant constituent in the sand fraction. The proportion of pumice increases abruptly at the two places marked VT, but in both cases the change is compensated by a progressive upward decrease in the pumice content of the overlying sediment.

B 132A

Alternating bands of muddy sand and sandy mud. Contacts between adjacent bands are sharp. Mineral grains are the main constituent in the sand fraction of the sandy mud. In the muddy sand, the coarse sand fraction consists mainly of pumice, while the fine sand fraction consists dominantly of mineral grains.

B 132B

Alternating bands of muddy sand and sandy mud. Contacts between adjacent bands are typically sharp. The muddy sand and sandy mud are virtually identical with the corresponding sediments in core B 132A, taken at approximately the same locality. Mineral grains are the main constituent in the sand fraction of the sandy mud. In the muddy sand, the coarse sand fraction consists mainly of pumice, while the fine sand fraction consists dominantly of mineral grains. (In Fig. 8 thin mud layers are drawn diagrammatically, the true thicknesses being given alongside.)

B 133

Sandy mud. Pumice is the dominant constituent in the sand fraction. There is a distinct increase in pumice content at VT, but this is compensated by a decrease at (V)T. Organic burrows are present in many places, and are particularly common in the band marked SO and MO. The burrows may be either sandier or muddier than the enclosing sediment.

B 134

Bands containing sand, mud, and pebbles in various proportions. Mineral grains predominate in the sand fraction, but a certain amount of pumice appears above VT.

B 135

Very sandy mud at the base, grading upwards into sandy mud at the top. Small pumice pebbles (mainly the white variety) are scattered throughout the core, but tend to be concentrated in particular zones (those marked PB). In the uppermost of these zones, the white pumice fragments range up to 8 mm in diameter, but elsewhere they do not exceed 3 mm. Occasional greywacke-suite pebbles up to 3 mm in diameter are found in the lower part of the core, but these are virtually absent from the upper part. Mineral grains predominate in the fine sand fraction, whereas pumice is dominant in the coarse sand and pebble fractions. Pockets of virtually pure fine-grained white pumice are common in various parts of the core.

B 137
This core shows a conspicuous upward transition from relatively coarse to relatively fine sediment. In the lower parts of the core, mineral grains are the dominant constituent in both the coarse and fine sand fractions. Mineral grains again dominate the fine sand fraction in the upper part of the core, but pumice and mineral grains are both important constituents in the coarse sand fraction.

B 143
Muddy sand, containing pumice fragments, shell fragments, greywacke-suite pebbles, and carbonised wood fragments in various proportions. Mineral grains predominate in the fine sand fraction, while pumice predominates in the coarse sand fraction.

B 144
Near the base, muddy sand with shell fragments up to 1 cm in diameter and occasional greywacke-suite pebbles up to 3 mm in diameter. This shows a broad upward gradation into pumiceous sandy mud, although there are numerous fluctuations in the proportion of sand. The proportion of shell fragments falls rapidly around (H)T, and the greywacke pebbles become progressively more rare, virtually disappearing about halfway up the core. The ratio of mineral grains to pumice in the sand fraction decreases progressively upwards, mineral grains being the main component near the base of the core, and pumice near the top.

B 145
Slightly sandy mud. Pumice is the main constituent in the sand fraction. The highest concentration of pumice occurs between VT and (V)T, where the fragments range up to 3 mm in diameter. Near the top of the core is a sharply defined band (marked VB) with a higher proportion of sand and a higher silt:clay ratio than the sediment above and below. Lamination is present, being most conspicuous in the upper part of the band.

B 146
Sandy mud. Pumice is the dominant constituent in the sand fraction. The proportion of pumice increases fairly abruptly about 13 in. above the base; from this point there is a fluctuating but progressive decrease in pumice content towards the top.

B 147
Slightly sandy mud. Pumice is the dominant constituent in the sand fraction. There is a general decrease in pumice content from the base to the top. Occasional white pumice fragments, up to a few millimetres in diameter, are present in the lower part of the core.

B 148
Very sandy mud near the base, grading upwards into sandy mud near the top. Mineral grains are the main constituent in the sand fraction, but a considerable quantity of pumice is also present.

B 149
Muddy sand, with numerous fragments of pumice up to 5 mm in diameter. The larger pumice fragments in PB belong dominantly to the white variety, but elsewhere white pumice is rare. Small shell fragments up to 5 mm in diameter are common below (H)T and in HB. A single large valve 5 cm in diameter is also present in HB. The plant fragments in GB are up to about 5 mm in diameter. Mineral grains predominate in the fine sand fraction, while pumice is the main constituent in the coarse sand and pebble fractions.

DISTRIBUTION AND NATURE OF SEDIMENTS

The sediments of Hawke Bay may be divided into five groups:

(1) Off-shore gravel zones.
(2) Off-shore sand belt.
(3) Mud belt.
(4) Central zone, consisting of pebbly muddy sand, pebbly mud, muddy gravel, muddy sand, and sandy mud.
(5) Sediments associated with the Lachlan Ridge; these include muddy sand, sandy mud, and gravel.

The distance between bottom-sampling stations is too great in most parts of the bay to define accurately the positions of the boundaries between the various groups, or to determine the sharpness of the boundaries. There is, however, local evidence that the boundaries between 1 and 2 and between 3 and 4 are relatively sharp, whereas that between 2 and 3 appears to be gradational. The characteristics of the five groups are described below. (The boundaries of the groups are shown on Figs. 9, 11, and 12.)

(1) Off-shore Gravel Zones

The larger zone, opposite the Mohaka River, runs for 15 miles parallel to the coast and extends from near the shore to a depth of 20-25 fathoms, whereas the smaller one opposite the Tukituki River runs for only 5 miles parallel to the coast and extends to a depth of only 10-15 fathoms. Nearly all samples were obtained by dredge or snapper grab, as the hard sediments are very unsuitable for coring; two cores a few inches long were in fact obtained, but these have been treated as surface samples. The samples all contain a large proportion of pebbles, and some contain cobbles, but these are accompanied by mud and sand whose bulk may exceed that of the coarser clasts. The latter are subangular to rounded, and are usually somewhat flattened. The b-diameter of the largest clasts in a particular sample varies considerably, ranging from about 2 cm to about 10 cm. Nearly all the clasts are derived from members of the Mesozoic greywacke sequence, but there also occur occasional pebbles of rhyolitic pumice evidently derived from the Quaternary volcanic province of Taupo.

In most samples the mud and sand fill the interstices between the larger clasts, but the finer sediment may be present in sufficient quantity to form a continuous matrix enclosing the pebbles.

(2) Off-shore Sand Belt

Muddy sand occupies a discontinuous zone extending from the coast to depths of 15-20 fathoms, and running from Cape Kidnappers to Mahia Peninsula (Fig. 9, 10). This zone, named the off-shore sand belt to distinguish it from the sandy sediments which occur in other parts of the Bay, will be referred to simply as the sand belt. The sand belt is interrupted by the two gravel zones. In addition, its outer boundary is very irregular in places, the most conspicuous irregularity being the long salient running south-eastward from a position about 3 miles north-east of Napier. This feature will be called the sand-belt salient, or more shortly the salient.

The sediment of the sand belt is very unsuitable for coring, as it resists penetration but at the same time is relatively incoherent and washes out of the corer barrel. Nearly all the samples collected were thus obtained by dredge, snapper grab, or Worzel sampler, cores being obtained only on the borders of the sand belt and the mud belt.

The main constituent of the sediment is fine sand, in the 250 μ to 66 μ grain-size range (Fig. 10). The coarser sand fraction forms a relatively small proportion of the sediment, and particles larger than 2 mm in diameter are very exceptional. Mud, on the other hand, is a more important constituent, ranging from about 7% to 50% of the sample, at which point the sediment becomes a sandy mud. The sand particles consist dominantly of subangular quartz, feldspar, glassy rhyolitic pumice, and fragments of members of the greywacke suite. The latter are sometimes stained brown with limonite, as a result of earlier subaerial weathering. Different varieties of quartz can be distinguished, but these also occur in the sediments of the mud belt and will be described under that heading. Small shells (mainly Foraminifera), shell fragments (mainly Mollusca), and plant fragments are nearly always present, but are rarely more than minor constituents. Non-vesicular semicrystalline rhyolite and granular rhyolitic tuff occur in most samples but are always minor constituents. Sedimentary rock fragments (usually sandstone, less commonly

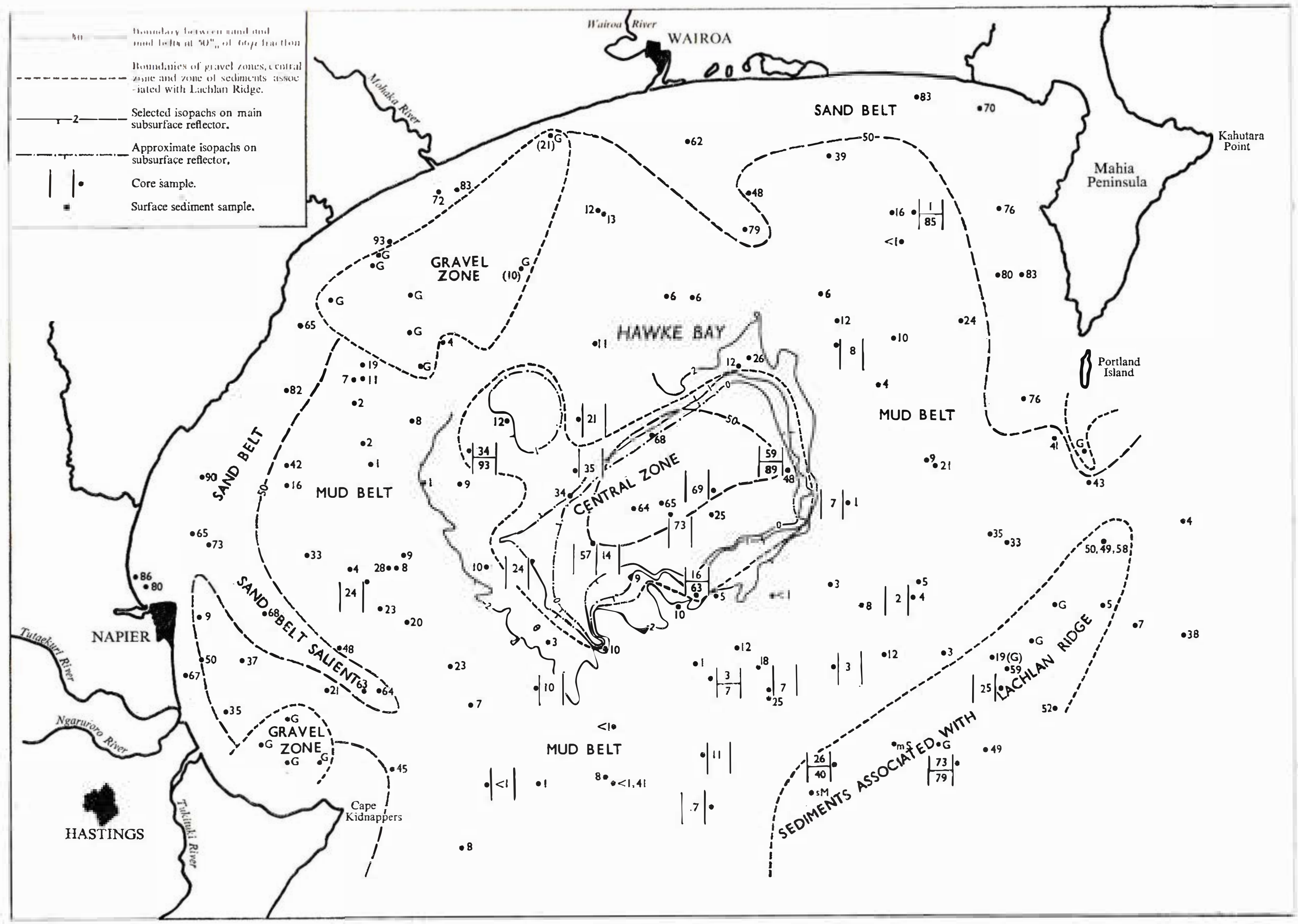


FIG. 9. Weight percentage of sediment with diameter more than 66 μ, uncorrected for the presence of aggregates: surface samples are indicated by simple numbers and core samples by numbers between vertical lines. Where two samples from the same core were analysed, the upper and lower samples are separated by a horizontal line. G = gravel.

mudstone) are frequently present in subordinate amounts: many of these fragments are relatively fresh, being light grey or green in colour, but some are stained brown by limonitic weathering. Accessory minerals include hypersthene, augite, hornblende, biotite, muscovite, magnetite, and ilmenite: these minerals are fresh and rarely show any sign of alteration. The same applies to these accessory minerals when they occur in the other sedimentary zones.

Grain counts from surface samples from the sand belt are given in Table 3.

Pumice, shell, and plant fragments show a strong tendency to be concentrated in the coarser sand grades, and pumice is usually dominant in fractions with a grain size in excess of ¼ mm. The sand in the ⅛ mm to 1/16 mm range, however, always consists dominantly of mineral grains (quartz, feldspar, and greywacke fragments).

In addition to single grains, the sediment may also contain a small proportion of multigranular aggregates; these are rounded or irregular in shape, and are composed principally of material similar to the bulk of the sediment. Many of the rounded aggregates are undoubtedly faecal pellets, but others have arisen from the alteration of particles of organic matter in the sediment (secretions, excretions, and fragments of tissue). Some of the irregular aggregates may also have been formed as a result of the alteration of organic particles (the shape thus being an original feature), but in many cases they must be due to the break-up of rounded aggregates during mechanical analysis. For convenience, those aggregates composed of material similar to the bulk of the sediment are herein called the "normal" type of aggregate. This type is much more abundant in the sediments of the mud belt

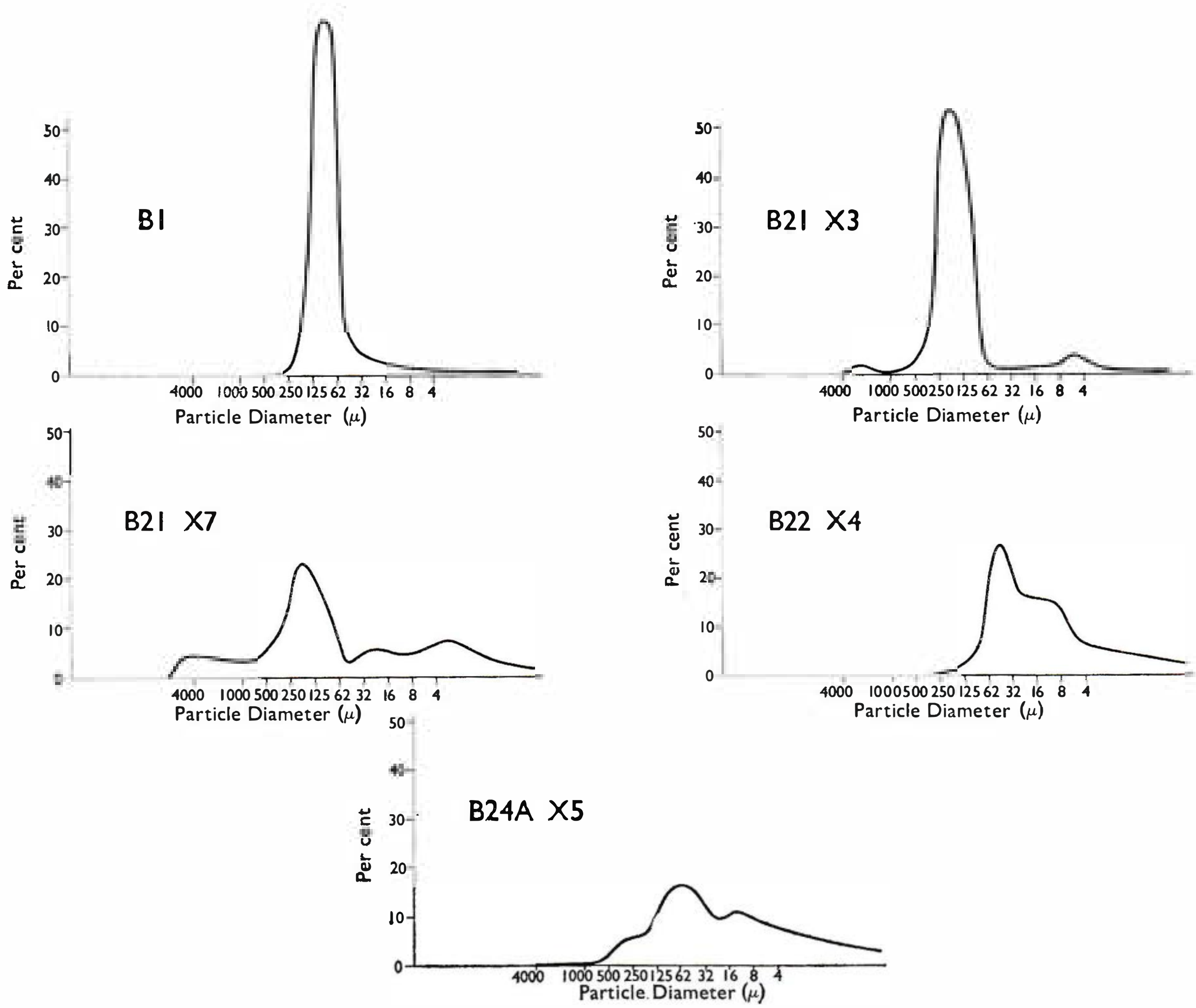


FIG. 10. Grain-size distributions within selected sediment samples.

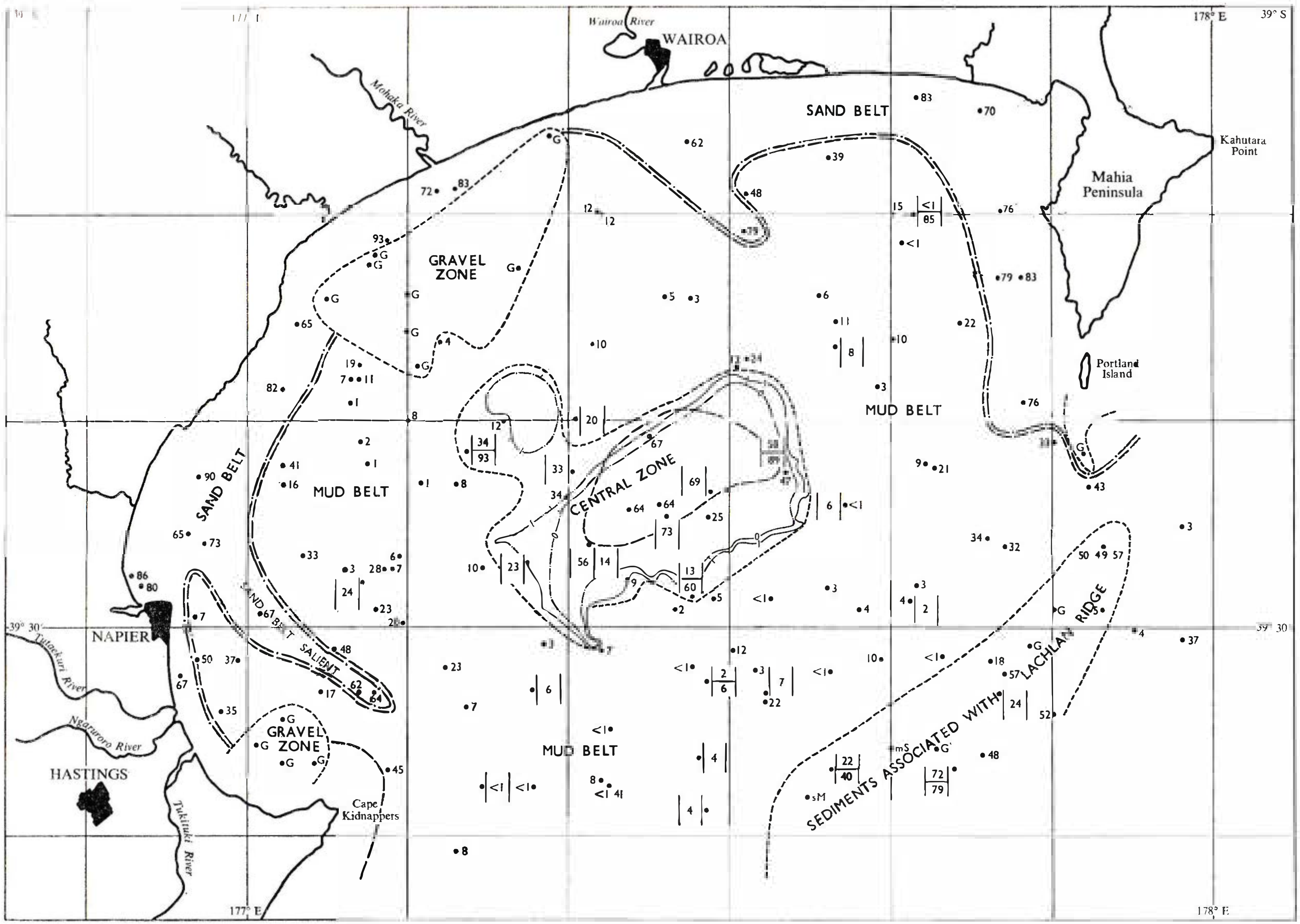


FIG. 11. Weight percentage of sediment with diameter more than 66 μ, corrected for the presence of aggregates: surface samples indicated by simple numbers and core samples by numbers between vertical lines. 50% contour indicated by broken line with dots. This contour has been given a slight arbitrary displacement towards the shore with respect to the 50% contour uncorrected for aggregates (broken line without dots). G = gravel.

and is described more fully under that heading. (Further comment is also made in the section on organic structures, p. 58.)

The sediments of the sand-belt salient also contain a small proportion of "green aggregates" and "brown aggregates", two varieties not found in the main part of the sand belt. The "green aggregates" are dark to medium green in colour, with a greasy lustre, and syneresis cracks are common. Although they show a considerable range of shape and composition, two basic morphological types or "morphotypes" can be distinguished: (i) spheroids and ovoids composed of relatively uniform fine-grained compact material; (ii) subangular grains with an irregular shape but rounded corners and edges, consisting of fine-grained compact material, which in some cases is mingled or interspersed with numerous larger silt or sand particles. The subangular grains are considerably more abundant than the spheroids and ovoids. Both morphotypes are frequently botryoidal, with syneresis cracks located between the bulges. These aggregates show no evidence of transport, and are evidently authigenic. The spheroids and ovoids are considered to be altered faecal pellets, and the subangular grains fragments of sedimentary rock. Pale green faecal pellets and sedimentary rock fragments can sometimes be identified, and these probably correspond to intermediate stages of alteration.

The green aggregates are glauconitic. The glauconite usually extends through the whole aggregate, but a few of the subangular grains contain a brown limonitic core surrounded by a glauconitic outer zone. These aggregates may thus be divided into two chemical types: those without limonite will be called chemotype 1, and those with a limonitic core will be called chemotype 2.

The brown aggregates range in colour from greenish-brown or yellowish-brown to deep brown or almost black. They have the same greasy lustre as the green aggregates, and syneresis cracks are likewise common. Two basic morphotypes can again be identified; spheroids and ovoids consisting of fine-grained compact material, and subangular grains composed of similar fine-grained material, which is mingled in some cases with sand or silt particles. The brown aggregates owe their colour to the presence of limonite. Most of them also contain glauconite, but the colour of the latter is masked to a greater or lesser extent by the limonite. Four chemotypes can be distinguished:

Chemotype 1. Both limonite and glauconite are scattered throughout the aggregate, although there is a tendency for the limonite to be concentrated near the periphery. This is the most abundant chemotype.

Chemotype 2. The core of the aggregate contains both limonite and glauconite, but the outer zone is entirely limonitic.

Chemotype 3. The outer zone contains both limonite and glauconite, but the core is entirely limonitic. This chemotype is confined to subangular grains.

Chemotype 4. The aggregate is limonitic throughout.

A noteworthy feature of the pumice grains in the sediments of the sand-belt salient is that, very exceptionally, the pumice vesicles are filled with compacted, medium- to dark-green material similar in appearance to that forming the green aggregates – normally in the Hawke Bay sediments the vesicles of pumice grains, if not empty, are filled with pale greenish-grey mud similar to that in the enclosing sediment.

(3) Mud Belt

Sandy mud covers most of the Bay outside the sand belt (Figs. 9, 10). Many of the samples in this area were obtained by dredge or Worzel sampler, but the sediment was also suitable for coring, and numerous piston cores were obtained, the longest being 9 ft 7 in. long.* The proportion of sand in the sediment varies very considerably, ranging from less than 1% to 50%. The sand particles include the same varieties as are in the sand belt, with subangular quartz, feldspar, greywacke fragments, and glassy rhyolitic pumice dominant. Shells, shell fragments, and plant fragments are commonly present, but usually form only a minor proportion of the sand fraction. Non-vesicular semicrystalline rhyolite and granular-rhyolitic tuff, similar to those found in the sand belt, are again regular but minor constituents. Accessory minerals include hypersthene, augite, hornblende, mica, magnetite, and ilmenite: hypersthene is the most abundant of these accessories.

The quartz grains may be divided into three main types: greenish, yellowish, and colourless. The greenish quartz is veined or partly coated with chlorite, and the yellowish with limonite. Yellowish-green grains coloured with both limonite and chlorite are numerous, but have been counted as "yellowish" or "greenish" on the basis of the predominant colour. The quartz grains are nearly all irregular in form, but occasionally the

* Dry lengths of cores are quoted except where otherwise stated.

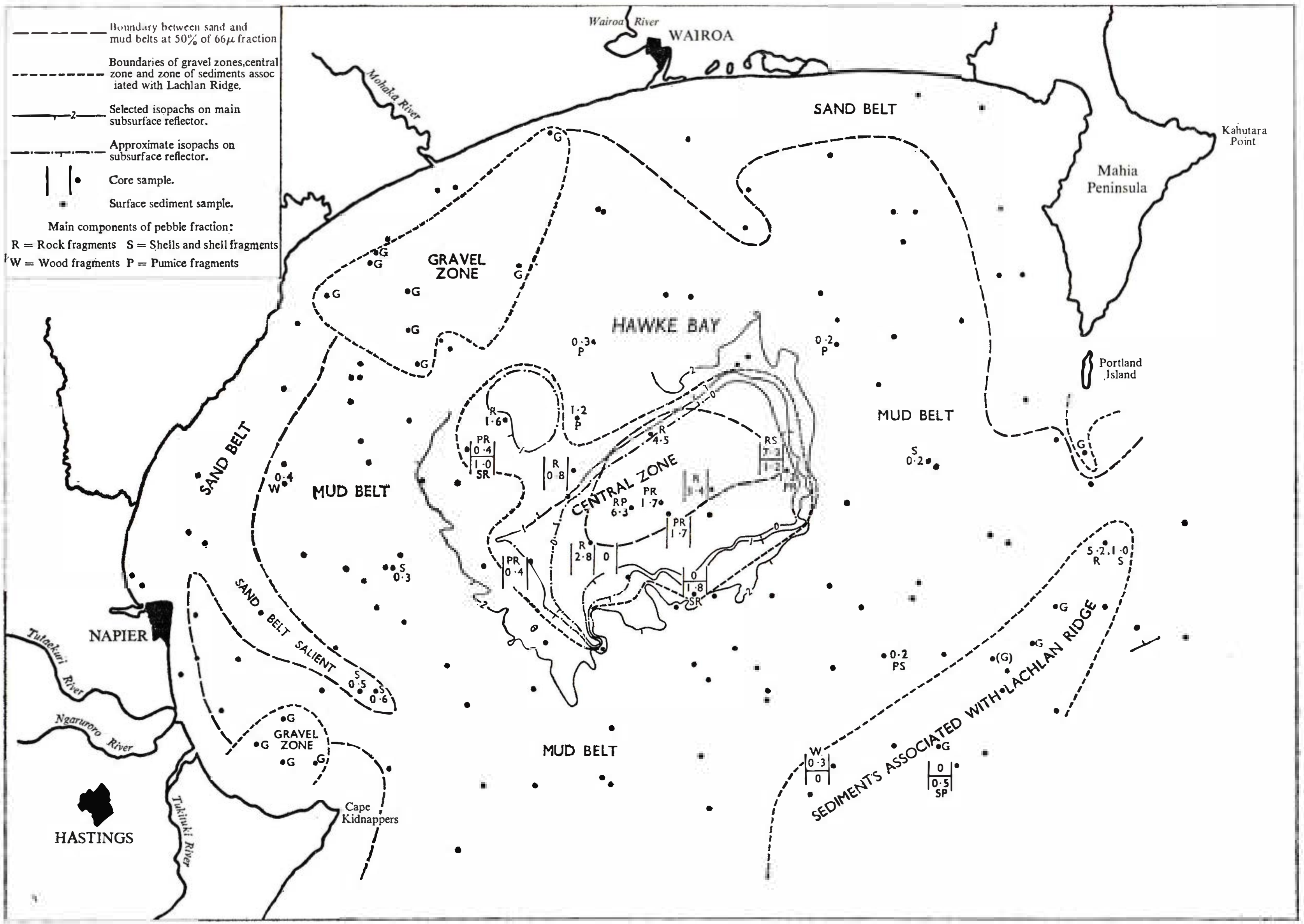


FIG. 12. Weight percentage of sediment with diameter more than 2 mm: surface samples indicated by simple numbers and core samples by numbers between vertical lines. G = gravel (dominantly rock fragments).

colourless variety take the form of euhedral hexagonal pyramids.

The feldspars are nearly always colourless and unweathered, but a yellowish and somewhat weathered variety is occasionally present in small numbers. The colourless feldspars are frequently euhedral, and sometimes carry remnants of adhering rhyolitic pumice; the yellowish feldspars, on the other hand, are typically subhedral, and show no adhering pumice.

The dark accessory minerals normally occur as small euhedral crystals; the hypersthene, augite, and hornblende form short prisms, whereas the magnetite is equidimensional and the ilmenite and mica are tabular. Small grains of magnetite are often attached to or embedded in the hypersthene prisms, and small quantities of pumice commonly adhere to hypersthenes or to hypersthene-magnetite aggregates.

The macroscopic colour of the pumice grains is usually pale greenish-grey due to fine sediment which clings to the rough surface of the grains and penetrates the vesicles. In a few cores, however, there are pumice grains that are almost white in colour; by contrast the fine sediment is easily removed from their surfaces and has scarcely penetrated the vesicles. Both greenish and white pumice may be present in the same core. There also occur sporadic grains of pumice in which the mud filling the vesicles is yellowish, presumably due to the presence of limonite.

Multigranular aggregates composed principally of material similar to that forming the bulk of the sediment are numerous. They consist chiefly of mud, usually accompanied by a minor amount of sand, and they may be rounded (typically ovoid) or irregular in shape. The surface of the rounded aggregates varies from quite smooth in some cases to relatively rough in others, with the grain-size of the material decreasing from the rough to the smooth varieties. It is sometimes possible to classify the rounded aggregates further as "smooth" or "rough", although the two varieties may not be sufficiently distinct to do this. The smooth rounded aggregates are undoubtedly faecal pellets, and owe their preservation during mechanical analysis to their greater degree of compaction than the surrounding sediment and to the presence of an organic matrix. The origin of the rounded aggregates with rough surfaces is more problematical (see also p. 58). Some of the rough rounded aggregates have no doubt originated from the abrasion of smooth aggregates, but there is also a class of "true" rough aggregates, which possess regular spheroidal or ellipsoidal outlines and have evidently suffered no significant abrasion. This is proved by the occurrence of samples in which the smooth and rough varieties are clearly differentiated, and where the presence of numerous well preserved smooth aggregates shows that no great number of rough aggregates can have arisen by abrasion. A distinctive feature of the rough rounded aggregates is their frequent possession of a core in which the grains are held together by a matrix of gypsum. This gypsum is usually compact with a resinous appearance, but it may also occur in a white fibrous form. Some of the irregular aggregates may be derived from the original sediment, but others are undoubtedly due to the break-up (as opposed to the abrasion) of smooth or rough rounded aggregates during mechanical analysis. On the other hand, the abrasion which also occurs during mechanical analysis would cause rounding of the irregular aggregates, and some of these would be converted to the rough rounded type.

Green and brown aggregates, similar to those in the sand-belt salient, are found in limited quantities in those parts of the mud belt flanking the salient.

Generalised counts of grain types from surface samples in the mud belt are included in Table 3. More detailed counts for 250–500 μ fractions from cores are given in Table 4 and generalised counts for 66–125 μ fractions from cores are given in Table 5.

Pumice tends to be concentrated in the coarser sand fractions and is frequently the major constituent in the 250 μ to 500 μ size range, whereas mineral grains are concentrated in the finer fractions and usually predominate in the 66 μ to 125 μ range. Plant fragments and shell show no obvious tendency to be concentrated in either the coarser or the finer fractions. The grain size of the larger clasts does not usually exceed 2 mm, but occasionally there occur small pebbles or greywacke or plant fragments up to about 5 mm in width, and pumice or shell fragments up to 1 cm in width. Exceptionally large fragments of pumice and carbonised wood were obtained in the dredge haul from Station B 4, the maximum long diameter of the pumice fragments being 5½ cm and that of the carbonised wood 4 cm.

Pipette analyses of selected samples show that the silt:clay ratio in the sediments of the mud belt varies from 90:10 to 55:45, but is usually in the region of 70:30. X-ray diffractometer analyses show that the clay-mineral components include illite, chlorite, and in some cases montmorillonite.

Cores from the mud belt frequently show

Table 3. Counts of Grain Types in Surface Samples.

Two hundred grains were counted in each sample. In all cases the fraction selected for counting was that containing the median diameter of the sand component.

Sample	*Fraction* (μ)	*Pumice Fragments*	*Plant Fragments*	*Mineral Grains*	*Aggregates (Normal)*	*Aggregates (Green)*	*Aggregates (Brown)*	*Shell*
A 34	66–125	14	6	10	158	—	—	12
A 35	125–250	9	1	1	145	—	—	44
A 129	66–125	25	15	14	137	—	—	9
B 1	62–125	4	—	192	—	—	—	4
B 2	66–125	—	—	196	—	—	—	4
B 3	250–500	28	43	55	62	—	—	12
B 4	62–125	121	15	50	11	—	—	3
B 5	66–125	28	148	11	5	—	—	8
B 6	66–125	99	24	59	—	—	—	18
B 7	66–125	16	26	153	—	—	—	5
B 8	62–125	5	—	191	1	—	—	3
B 9	62–125	2	1	196	—	—	—	1
B 10	66–125	35	15	129	13	—	—	8
B 11	66–125	50	63	51	32	—	—	4
B 12	66–125	58	5	130	4	—	—	3
B 13	66–125	13	4	180	—	—	—	3
B 14	66–125	1	1	194	—	—	—	4
B 15	66–125	11	2	182	—	—	—	5
B 16	66–125	41	55	56	43	—	—	5
B 17	66–125	50	10	111	21	—	—	8
B 18	66–125	7	1	191	—	—	—	1
B 19	125–250	181	4	12	—	—	—	3
B 20	125–250	128	38	29	—	—	—	5
B 21	125–250	134	5	54	7	—	—	—
B 22	66–125	71	74	19	29	—	—	7
B 23	125–250	110	12	59	10	—	—	9
B 24	125–250	118	4	61	7	—	—	10
B 25	125–250	172	11	6	7	—	—	4
B 37	66–125	10	—	184	—	—	—	6
B 38	66–125	10	—	187	1	—	—	2
B 39	66–125	73	76	11	29	—	—	11
B 40	66–125	92	41	42	14	—	—	11
B 42	66–125	20	—	170	1	—	—	9
B 43	66–125	6	2	188	—	—	—	4
B 44	66–125	5	1	188	2	1	1	2
B 45	66–125	6	15	128	46	—	—	5
B 46	66–125	52	108	28	6	—	—	6
B 47	125–250	136	17	36	3	—	—	8
B 48	125–250	70	1	125	2	—	—	2
B 49	125–250	128	4	64	—	—	—	4
B 50	66–125	18	14	161	3	—	—	4
B 51	66–125	6	11	173	—	—	—	10
B 52	125–250	4	2	111	46	6	5	26
B 54	66–125	1	2	182	5	—	—	10
B 55	66–125	37	6	149	—	—	—	8
B 56	125–250	102	18	50	22	—	—	8
B 57	66–125	68	7	99	16	—	—	10
B 58	125–250	145	1	51	—	—	—	3
B 59	66–125	56	4	80	47	—	—	13
B 60	66–125	17	6	12	151	—	—	14
B 61	66–125	23	10	76	80	—	—	11
B 62	66–125	6	18	21	142	—	—	13
B 63	66–125	1	10	159	24	—	—	6
B 138	66–125	44	14	134	2	—	—	6
B 139	66–125	—	—	195	—	—	—	5
B 141	66–125	4	—	193	—	—	—	3
B 142	66–125	2	1	197	—	—	—	—
B 151	125–250	100	—	57	1	12	12	18
C 826	125–250	106	—	93	—	—	—	1
C 827	125–250	109	29	26	23	—	—	13
C 828	66–125	66	2	106	3	5	3	15
Z 302	66–125	8	—	189	—	—	—	3
Z 303	66–125	1	—	196	—	—	—	3
Z 304	66–125	20	7	165	1	—	—	7
Z 305	66–125	—	1	187	2	—	—	10
Z 306	66–125	7	6	179	5	—	—	3
Z 359	66–125	45	21	91	7	—	—	36
Z 361	66–125	73	32	62	14	—	—	19

Table 3—*continued*

Sample	*Fraction (μ)*	*Pumice Fragments*	*Plant Fragments*	*Mineral Grains*	*Aggregates (Normal)*	*Aggregates (Green)*	*Aggregates (Brown)*	*Shell*
Z 362	66–125	10	1	188	—	—	—	1
Z 363	125–250	133	3	56	1	—	1	6
Z 364	125–250	101	1	94	—	—	1	3
Z 365	66–125	98	41	56	3	—	—	2
Z 366	125–250	93	2	102	—	—	—	3
Z 367	66–125	11	7	177	2	—	—	3
Z 368	66–125	53	94	43	2	—	—	8
Z 369	66–125	28	14	146	5	—	—	7
Z 370	125–250	71	41	61	18	—	—	9
Z 371	66–125	50	13	129	6	—	—	2
Z 372	66–125	70	74	39	11	—	—	6
Z 373	125–250	10	3	160	4	5	1	17
Z 374	66–125	33	27	126	10	—	—	4
Z 376	66–125	22	11	162	—	—	—	5
Z 377	66–125	92	70	29	1	—	—	8
Z 379	125–250	60	21	26	86	—	—	7
Z 380	125–250	191	3	5	1	—	—	—
Z 381	125–250	3	2	177	—	3	1	14
Z 382	66–125	22	11	143	19	—	—	5
Z 383	125–250	88	4	87	8	—	—	13
Z 384	66–125	65	7	40	85	—	—	3
Z 385	66–125	33	9	90	62	—	—	6
Z 386	66–125	20	3	110	64	—	—	3
Z 387	66–125	27	49	40	80	—	—	4
Z 388	66–125	17	2	178	—	—	—	3
Z 389	66–125	90	22	75	5	—	—	8
Z 392	66–125	9	2	184	—	—	—	5
Z 393	66–125	33	9	147	1	—	—	10
Z 394	66–125	131	28	35	—	—	—	6
Z 395	66–125	77	10	102	2	—	—	9
Z 396	66–125	80	49	63	2	—	—	6
Z 405	125–250	149	8	33	—	—	—	10
Z 408	125–250	100	1	95	3	—	—	1
Z 409	66–125	113	10	51	—	—	—	26
Z 411	125–250	19	1	134	31	—	—	15
Z 413	66–125	58	4	113	9	—	—	16
Z 415	66–125	41	1	138	—	5	6	9
Z 416	66–125	70	19	58	43	—	—	10
Z 418	66–125	14	2	179	2	—	—	3
Z 419	66–125	6	10	160	9	—	—	15
Z 734	125–250	126	31	21	22	—	—	—
Z 735	125–250	69	21	15	89	—	—	6
Z 736	66–125	82	79	29	3	—	—	7
Z 737	125–250	116	6	27	46	—	—	5
Z 775	66–125	13	20	131	34	—	—	2
Z 776	66–125	1	—	197	—	—	—	2
Z 777	66–125	77	18	95	—	—	—	10
Z 778	66–125	25	2	167	2	—	—	4

Table 4. Counts of Grain Types in 250-500 μ Fractions from Cores.
(Three hundred grains were counted in each sample).

Sample Number	*Pumice (rhyolitic)*	*Glass (rhyolitic)*	*Greywacke fragments (+ subordinate argillite)*	*Sedimentary rock fragments (other than greywacke and argillite)*	*Shells and shell fragments*	*Plant Fragments*	*Aggregates (rough rounded)*	*Aggregates (smooth rounded)*	*Aggregates (rounded undifferentiated)*	*Aggregates (irregular)*	*Quartz (colourless)*	*Quartz (yellowish)*	*Quartz (greenish)*	*Feldspar (colourless)*	*Feldspar (yellowish)*	*Semicrystalline rhyolite*	*Rhyolitic tuff*	*Hypersthene*	*Augite*	*Hornblende*	*Other Types*
B21, X3	16	1	141	4	59	5	2	2	—	—	7	17	16	26	1	1	1	—	—	—	1 dark glass
B21, X7	157	3	40	4	24	2	—	—	—	—	3	11	6	26	—	14	6	2	—	—	1 dark pumice 1 dark glass
B22, X4	193	—	1	—	18	83	—	1	—	1	—	—	—	1	—	—	—	1	—	—	1 biotite
B23, X	5	1	—	—	6	11	80	13	—	157	1	7	1	4	8	—	3	—	2	1	—
B24A,X5	94	5	3	21	56	2	1	3	—	4	1	—	—	24	—	3	14	1	—	—	2 dark pumice, 2 red brown glass. 19 green aggregates 45 brown aggreg.
B122, X	7	—	—	—	21	13	—	—	171	80	—	—	—	2	—	5	1	—	—	—	—
B123, X	149	—	—	—	—	4	—	—	28	89	—	—	2	6	—	15	7	—	—	—	—
B124, X	49	—	—	—	36	197	—	—	8	6	—	—	—	—	—	—	1	—	1	—	2 biotite
B125, X	158	—	7	—	1	5	—	—	18	24	1	5	8	33	—	26	11	1	—	—	1 dark pumice, 1 magnetite
B126A,X	176	4	2	—	—	1	—	—	1	1	2	5	5	50	—	28	15	6	3	—	1 dark glass
B126B,X	77	—	—	—	21	35	72	48	—	40	—	1	—	5	—	1	—	—	—	—	—
B127, X	229	—	5	—	1	4	7	1	—	3	1	3	5	22	—	9	6	3	—	1	—
B128, X	241	—	—	—	7	—	—	—	5	2	—	—	1	18	—	14	10	1	—	—	1 dark pumice
B129, X	95	—	—	—	14	4	—	—	24	129	—	—	—	10	—	11	12	1	—	—	—
B132A,Y	260	—	—	—	31	1	—	—	1	3	—	1	—	—	—	2	—	—	1	—	—
B132A, Z	3	—	—	—	28	145	—	—	26	41	5	17	—	14	5	2	7	—	2	5	—
B133, X	105	—	—	—	8	110	53	2	—	16	—	—	—	4	—	1	—	—	—	—	1 biotite
B134, X	126	5	70	—	25	3	—	—	4	1	5	18	13	15	—	5	8	2	—	—	—
B135, X	283*	—	—	—	2	7	—	—	—	—	—	—	—	6	—	2	—	—	—	—	—
B137, X1	141	6	32	—	15	11	11	—	—	—	1	5	7	29	—	16	20	5	1	—	—
B137, X2	1	—	115	—	56	—	—	—	—	—	13	21	28	53	2	2	2	3	1	2	1 dark glass
B143, X	201	9	3	—	7	1	1	1	—	—	—	1	1	34	—	18	18	4	—	—	1 dark pumice
B144, X1	184	9	1	—	6	2	—	—	12	18	—	—	—	25	—	22	20	1	—	—	—
B144, X2	38	4	13	—	133	8	12	—	—	42	3	2	3	23	—	2	4	4	1	—	8 dark pumice
B145, X	41	—	3	—	24	139	18	1	—	54	2	5	—	4	1	1	4	—	2	—	1 muscovite
B145, Y	3	—	10	—	25	116	—	—	—	15	20	17	7	54	29	—	1	—	1	2	—
B146, X	171	6	—	—	1	2	36	22	—	29	—	—	—	10	—	15	7	—	—	—	1 dark lava
B147, X	119	3	1	—	7	8	50	19	—	45	1	—	—	14	—	16	11	4	—	—	1 dark pumice 1 dark glass
B148, X1	152	17	—	—	8	1	13	18	—	24	4	—	—	38	—	8	12	1	2	1	1 dark pumice
B148, X2	136	5	2	—	12	12	12	21	—	72	—	1	—	21	—	6	—	—	—	—	—
B149, X1	167	1	5	6	9	1	1	2	—	4	—	1	—	38	1	10	17	1	—	1	2 dark pumice, 1 dk glass. 22 green aggr. 10 brown aggr.
B149, X2	119	—	1	3	145	11	—	—	—	—	—	—	—	12	—	1	5	—	—	—	1 biotite. 1 green aggr., 1 brown aggr.

*252 greenish, 31 white

Table 5. Counts of Grain Types in 66-125 μ Fractions from Cores.
(Three hundred grains were counted in each sample.)

Sample	*Pumice Fragments*	*Plant Fragments*	*Mineral Grains*	*Aggregates (Normal)*	*Aggregates (Green)*	*Aggregates (Brown)*	*Shell Fragments*
B21 X3*	1	1	296	—	—	—	2
B21 X7*	166	7	112	2	—	—	13
B22 X4*	53	20	188	4	—	—	35
B23 X	18	4	220	45	—	—	13
B24A X5*	13	—	269	6	1	1	10
B122 X	5	41	153	93	—	—	8
B123 X	81	34	93	68	—	—	24
B124 X	8	11	273	1	—	—	7
B125 X	20	8	249	17	—	—	6
B126A X	13	1	281	3	—	—	2
B126B X	98	13	173	11	—	—	5
B127 X	37	5	220	24	—	—	14
B128 X	212	4	55	15	—	—	14
B129 X	41	2	22	222	—	—	13
B132A Y	28	1	251	1	—	—	19
B132A Z	25	52	132	84	—	—	7
B133 X	178	27	65	25	—	—	5
B134 X	25	2	261	8	—	—	4
B135 X	64	7	192	28	—	—	9
B137 XI	30	5	259	2	—	—	4
B137 X2	2	—	297	—	—	—	1
B143 X	8	—	281	9	—	—	2
B144 X1	100	2	116	72	—	—	10
B144 X2	7	3	286	—	—	—	4
B145 X	175	7	83	9	—	—	26
B145 Y	128	82	25	61	—	—	4
B146 X	65	1	31	184	—	—	19
B147 X	124	11	25	127	—	—	13
B148 X1	32	1	192	66	—	—	9
B148 X2	11	—	272	10	—	—	7
B149 X1	13	1	242	31	3	1	9
B149 X2	—	—	290	—	3	2	5

**The lower size limit for these samples was 62 μ.*

Table 6. **Fraction Containing Median Diameter of Sand Component in Samples from Cores.**

Core No.	*Subsample*	*Fraction containing median sand diameter* μ
B 21	X 3	125–250
B 21	X 7	125–250
B 22	X 4	62–125
B 23	X	66–125
B 24A	X 5	62–125
B 122	X	66–125
B 123	X	250–500
B 124	X	66–125
B 125	X	66–125
B 126A	X	125–250
B 126B	X	66–125
B 127	X	125–250
B 128	X	125–250
B 129	X	66–125
B 132A	Y	66–125
B 132A	Z	66–125
B 133	X	66–125
B 134	X	125–250
B 135	X	66–125
B 137	X 1	125–250
B 137	X 2	125–250
B 143	X	125–250
B 144	X 1	125–250
B 144	X 2	125–250
B 145	X	66–125
B 145	Y	66–125
B 146	X	66–125
B 147	X	125–250
B 148	X 1	66–125
B 148	X 2	66–125
B 149	X 1	125–250
B 149	X 2	125–250

gradational changes from one part to another, but abrupt variations are rarely found and well defined banding or lamination* is also exceptional. A type of banding with individual layers up to several centimetres thick is relatively common, but the layers are usually very diffuse, and no lamination is visible within the larger units (Plate 2, c). Well defined stratification was found at only four of the 13 coring localities in the mud belt. Two of these localities (core B 124 and cores B 132 A-B) were situated near the mutual boundary of the mud belt and sand belt; the third (core B 22) was located not far from the eastern limit of the central zone, while the fourth (core B 145) was located in the outer part of the mud belt.

Cores B 132 A-B show well developed banding, with sharply defined alternating bands and laminae of coarser and finer sediment (Fig. 12). Individual units range from a few millimetres up to several centimetres. The coarser bands consist predominantly of muddy sand, while the finer bands consist mainly of muddy sand with a more uniform aspect than the typical sediments of the mud belt. These muddy bands occasionally show internal lamination due to the presence of thin alternating layers of sediment slightly coarser or finer than the average. Two types of lamination are visible in core B 132 B, one type being on a scale of about 2–5 mm per double unit, and the other on a scale of 0·1–0·3 mm. Core B 132 A shows only the 2–5 mm type of lamination. Core B 124 consists of sandy mud with a variable proportion of sand. Banding is on a scale of several centimetres, but the bands are generally indistinct and have diffuse boundaries. However, a well developed lamination on a scale of about 2–6 mm is visible in some parts of the core, and there may also be a finer lamination on a scale of 0·1–0·5 mm. The sediments in core B 22 consist predominantly of slightly sandy mud similar to that found in the rest of the mud belt, showing no well defined stratification. Near the top of the core, however, is a sharply defined band containing a higher proportion of sand than the sediments above and below. This band has an abrupt top and bottom, and is about 2½ in. thick; the lower part shows faint lamination. A sharply defined band which occurs near the top of core B 145 is also about 2½ in. thick, and the upper and lower contacts are abrupt. Lamination is present throughout the band, and becomes more conspicuous towards the top: individual laminae are about 1 mm thick. The band has a higher proportion of sand and a higher silt:clay ratio than the sediment above and below. It is probably the same age as the very similar band near the top of core B 22.

The commonest structures in the cores are infilled organic burrows, principally worm-tubes (Plate 2, a; Plate 3, b). These irregular tubular zones or rounded pockets, with a circular or elliptical cross-section, are composed of material differing somewhat from the enclosing sediments. The diameter of these burrows is up to about 1 cm, but is normally 3–4 mm. The sediment within the burrows is usually differentiated by grain size, being either coarser or finer than the enclosing material. When the sediment contains the white variety of pumice, there may occur burrows whose constitution is strikingly different from the enclosing material. This type of pumice may occur not only scattered through the sandy mud, but also as thin irregular layers or pockets composed almost entirely of white volcanic ash, whose colour provides a sharp contrast with the greenish-grey sandy mud forming the bulk of the

* "Banding" is used here for layering on a scale of 1 cm or more, while "lamination" is used for layering on a scale of less than 1 cm.

sediment. White burrows filled with pumice may occur in the sandy mud, and greenish-grey burrows filled with sandy mud in the ash layers. These provide some of the clearest examples of organic burrowing in the sediments of the mud belt.

Although lamination and organic burrows may be present in the same portion of sediment, the two types of structure tend to be mutually exclusive. There are, in addition, large portions of the sediment in which neither is visible, and the only identifiable small-scale structures are diffuse and irregular patches of sediment, which may be coarser or finer than the surrounding material. This texture will be called "mottling" (Plate 3, c).

Over most of the mud belt the sediments are fairly uniform in vertical section, but near the outer and inner borders of the belt vertical variation becomes more pronounced. Cores bordering on the sand belt show interbanded finer and coarser layers, the most conspicuous examples of this being seen in cores B 132A and B 132B. Again, cores near the central zone show a pronounced downward increase in the proportion of sand, and small pebbles begin to appear, the sediment thus becoming a pebbly mud.

Samples from two localities in the mud belt were submitted to the New Zealand Institute of Nuclear Sciences for ^{14}C analysis. The results are as follows:

Station B 4 (surface sample)

Carbonised wood from sandy mud (surface sample).

NZ-113. Age: 2,030 ± 100 years before 1950 (Grant-Taylor and Rafter, 1963).

Station B 23 (base of core)

Organic carbon and carbonate from sandy mud (base of core).

Sample No. R335/2A (organic carbon). Age: 8,600 ± 350 years B.P.

Sample No. R335/2B (carbonate). Age: 15,000 ± 300 years B.P.

The boundary between the sand belt and the mud belt can be defined in two ways, depending on whether the sediments are treated in terms of their present composition (as determined by mechanical analysis), or their probable mechanical composition during transport. The two definitions are not equivalent, since in each belt the sand component contains aggregates that have not been transported into place, but have developed within the sediment. Using the first definition the 50% contour for the 66 μ size fraction W_x will therefore be taken as the boundary of the sand belt and mud belt. The >66 μ fraction represents the sand component (together with very occasional small pebbles), and the <66 μ fraction represents the mud component. The boundary thus corresponds to a transition from muddy sand to sandy mud. The occasional pebbles in the >66 μ fraction do not affect the terminology, as they never represent more than 2% by weight of the sediment.

The transition from the sand belt to the mud belt clearly corresponds to a general decrease in sediment grain size away from the shore. This is evident not only if the boundary is drawn with respect to the present composition of the sediments, but also if it is drawn in terms of the probable composition of the sediments during transport. The weight percentage of the >66 μ fraction during transport (W_t) can be determined approximately by regarding any normal aggregates present as undispersed sediment, and calculating the mechanical composition that the sediment would have if these aggregates were removed. The calculation is made as follows.

Approximate relative densities are first assigned to the main types of sand grain. The relative densities used in the present case are given below.

Grain Type	Relative Density
Mineral grains (includes only discrete non-vesicular mineral grains)	3
Pumice fragments	2
Shell fragments	1
Plant fragments	½
Aggregates (normal)	2½

The weight fraction of aggregates in the sand fraction (A) is then calculated from the formula:

$$A = \frac{2\frac{1}{2}N_a}{3N_m + 2N_v + N_h + \frac{1}{2}N_g + 2\frac{1}{2}N_a}$$

where N_m, N_v, N_h, N_g, and N_a are respectively the numerical proportions of mineral grains, pumice fragments, shell fragments, plant fragments, and aggregates. The proportions of the various grain types in the sand fraction as a whole are given approximately by their relative abundance in the particular size range that spans the median diameter of the sand fraction. For surface samples, counts were made on the appropriate size fraction (Table 3). For core samples, standard counts (see Tables 4 and 5) were made on the 66–125 μ and 250–500 μ fractions, the average of these two counts being used for samples with a median sand diameter in the 125–250 μ range (Table 6). As some of the green and brown aggregates apparently represent altered faecal pellets, while others represent altered sedimentary rock fragments, they are added together and the total divided equally between N_m and N_a.

Once the value of A has been calculated, the value of W_t can be determined from the formula:

$$W_t = \frac{100\ W_x\ (1-A)}{100-W_xA}$$

where W_x is the present weight percentage of the $>66\,\mu$ fraction. Values for W_t are plotted in Fig. 11, together with a 50% contour for W_t and the 50% contour for W_x taken from Fig. 9. The W_t contour is given a slight arbitrary displacement with respect to the W_x contour, but in fact the W_t values near the boundary differ so little from the corresponding W_x values that the displacement is hardly significant.

(4) Central Zone

Pebbly muddy sand, pebbly mud, muddy gravel, muddy sand and sandy mud occupy an irregular zone about 15 miles wide in the middle of the bay (Figs. 9, 10, 12). A few samples were obtained by dredge or Worzel sampler, but several cores were also obtained, the longest being 8 ft 1 in. in length. These cores show that the above sediments occur as components in a layer, herein termed the central-zone layer, underlying the sediments of the mud belt. The maximum thickness of this layer is uncertain, as no core penetrated it from top to bottom. The component sediments form units up to about 2 ft thick, and may show either abrupt or gradational contacts. The successions observed in different cores are not sufficiently similar to allow cross-correlations within the layer itself, but near the top of the layer there is a consistent transition upwards from pebbly mud to the sandy mud (with very occasional pebbles) belonging to the mud belt. This transition takes place over a thickness of about 3 ft. The base of the layer is seen only in one core (B 21), in which 1 ft of pebbly muddy sand grades rapidly downward into several feet of sand containing a much smaller proportion of pebbles and mud (Fig. 10). This underlying sand is very similar to the sediments of the sand belt, although it is slightly coarser in grain and contains a considerably higher proportion of shell. As far as can be ascertained from the available samples, it does not crop out on the sea bed.

Two samples of shell were taken from core B 21, one representing material from the upper half of the sandy portion of the core, and the other material from the lower half. These were submitted for ^{14}C analysis to the New Zealand Institute of Nuclear Sciences, and the age determinations are as follows:

R. 688/1. (Upper sample.) 10,000 ± 450 years B.P.

R. 688/2. (Lower sample.) 10,250 ± 180 years B.P.

The pebbles in the sediments of the central zone consist of greywacke, pumice, shells and shell fragments, and plant fragments, in that order of abundance. Some of the plant fragments are carbonised wood. The largest greywacke pebbles, which occur in bands of muddy gravel, reach 3 cm in diameter, but those in the pebbly mud do not usually exceed 1 cm. The greywacke pebbles are usually subangular, but their shape varies to some extent according to size, the smaller ones tending to be equidimensional and many of the larger ones somewhat flattened. The largest pumice, shell, and plant fragments are in the pebbly muddy sand and pebbly mud, and reach maximum diameters of about 1 cm in each case. The pumice fragments are usually rounded and are often somewhat flattened, whereas the plant fragments tend to be subangular and are frequently either flattened or elongated. The shell fragments are highly angular.

The sand fraction is very similar in mineral composition to the corresponding fractions in the mud belt (Tables 3, 4, 5). Quartz, feldspar, greywacke, and glassy rhyolitic pumice are the dominant types, and the greenish, yellowish, and colourless varieties of quartz may again be distinguished. The quartz grains are mainly irregular in shape, but some of the colourless ones are euhedral hexagonal pyramids, similar to those in the mud belt but considerably more abundant. The euhedral crystals sometimes contain small rounded or tabular hollows, which probably represent corrosion pits. Pumice has not been found adhering to these quartz grains, which differ in this respect from the feldspars.

As in the mud belt, shells, shell fragments, and plant fragments are common, but are usually only minor constituents. Non-vesicular semicrystalline rhyolite and granular rhyolitic tuff are again present in small quantities. The accessory minerals are similar to those of the mud belt and include hypersthene, augite, hornblende, and iron ore.

Both the rounded and irregular types of normal aggregate are present in the central zone, although they are less common than in the mud belt. Green and brown aggregates also occur in small numbers, but these are considered to be derived, for the following reasons. (1) They are more often rounded than the green and brown aggregates in the sand-belt salient, and are rarely botryoidal. (2) When syneresis cracks are present, the cracks usually show no relation to the external form of the aggregates.

Most infilled pumice vesicles in the lower part of the central-zone layer contain pale greenish-grey mud similar to that in the enclosing sediment, although yellow limonitic infillings are also occasionally found. In the uppermost part of the layer, however, yellow limonitic infillings are common, and the whole sediment takes on a slightly yellowish tinge, although the yellow shade is far less pronounced than in the vesicles. This uppermost band extends downwards to a maximum depth of 3 ft below the surface of the central zone. Rare pumice vesicles filled with medium-to dark-green glauconitic material are also present in this band.

In the sediments of the central zone there is no obvious concentration of any particular grain type in a given size range. This is in contrast to the sand belt and mud belt, where the ratio of pumice to mineral grains rises with increasing grain size.

Organic burrows are very common in the finer-grained sediments of the central zone, and are the predominant type of small-scale structure in these sediments, but lamination is occasionally present; the lower portions of cores B 125 and B 127 both contain bands of muddy sand showing two types of lamination, one on a scale of 3–5 mm and the other on a scale of only 0.2–0.5 mm. In the coarser central-zone sediments, on the other hand, organic burrows are rarely discernible, and although the sediments may form individual layers down to about 1 cm in thickness, they show no lamination similar to that in the finer-grained sediments.

The area occupied by sediments of central-zone type coincides approximately with the area in which the main subsurface reflector lies at 1 fathom or less below the sea-bed. The boundary of the zone is defined mainly by the area in which the characteristic sediment assemblage appears in surface samples or in cores, but in a few sectors the boundary is extended to include those areas where the depth of the reflector below the surface is 1 fathom or less. There can be little doubt that the main reflector represents a rapid downward transition from the relatively fine-grained sediments of the mud belt into the much coarser sediment of the central-zone layer.

The distances of the various reflectors below the sea-bed can be estimated by measuring the appropriate intervals on the echo-sounding records, providing that the velocity of sound in the sediments of the mud belt is known. The velocity of sound in most unconsolidated sediments is not very different from its velocity in sea water, and on the assumption that this rule can be applied to the sediments of the mud belt, isopachs have been drawn for the depth (H_r) of the main reflector below the sea-bed (Fig. 6). These will also correspond to approximate isopachs for the thickness (H_m) of mud-belt sediments above the central-zone layer, but since the central-zone assemblage appears at the sea-bed while the effective depth of the reflector is still 1 fathom or slightly more, H_m will be taken as H_r—1 fathom.

The isopachs are limited to the area in which the main reflector can be distinguished. This area surrounds the central zone and covers a large part of the mud belt, but overlaps to an insignificant extent on to the Lachlan Ridge and does not reach the sand belt or gravel zones.

Table 7. Characteristics of Pebbles in Sediments Associated with Lachlan Ridge

Sample	Lithology	Size	Weathering
Z 390	Mainly pale greenish-grey mudstones, with subordinate pinkish-grey mudstone and laminated micaceous sandstones. All of these rock types may be calcareous, and the sandstones may be glauconitic.	Normal width 1–2 cm, maximum long diameter > 5 cm.	Brown weathering is apparent on the surface of some pebbles, but is not very conspicuous and may affect only one or two facets of a given pebble.
Z 391	Mainly pale greenish-grey mudstones, with subordinate gritty sandstone. The mudstones are sometimes calcareous, although less so than in Z 390, and the sandstones may be glauconitic.	Normal width 1–2 cm, maximum long diameter > 3 cm.	Brown weathering is occasionally present. It is less common on mudstone than in Z 390 but is more common on sandstone.
B 150	Greenish-grey calcareous mudstone. (Very rare greywacke.)	Normal width 3–4 mm, maximum long diameter 1 cm.	Brown weathering is ubiquitous and often permeates the whole of a particular fragment. In cases where the weathering is less complete, the brown layer may be patchy or concentrated on one facet of the pebble.

(5) Sediments Associated with the Lachlan Ridge

LACHLAN RIDGE GRAVELS

Dredgings of sandy gravel were obtained from three stations: Z 390, Z 391, and B 150. In each case, the pebbles consist of angular sedimentary rock fragments. The general characteristics of these pebbles and of the sand and mud fractions are shown in Tables 7 and 8.

The mudstone and sandstone fragments have the same general characteristics as the fragments of mudstone and sandstone in the gravel fraction. The single mineral grains are characteristically euhedral, and in this and other respects are very similar to the corresponding minerals in the sand belt, mud belt and central zone. The pumice, semicrystalline rhyolite, and granular rhyolitic tuff are again very similar to the corresponding types in the other sedimentary zones. The shell material again consists of Foraminifera (conspicuously worn in B 150) and broken mollusc shells.

Table 8. Characteristics of Sand and Mud Fractions in Sediments Associated with Lachlan Ridge

Sand fractions

(Dominant types †, subordinate and accessory types *)

Grain Types	Z 390	Z 391	B 150
Mudstone fragments	†	†	†
Sandstone fragments	*	*	—
Pumice fragments	*	*	*
Greywacke fragments	*	*	*
Semicrystalline rhyolite	*	*	*
Granular rhyolitic tuff	*	*	*
Feldspar	*	*	†
Quartz	*	*	*
Hypersthene	*	*	*
Augite	—	*	*
Hornblende	—	—	*
Magnetite	*	*	*
Ilmenite	—	*	*
Shell	*	*	†

Mud fractions (very minor in bulk)

Z 390	Z 391	B 150
Pale yellowish-grey: silt and clay.	Pale yellowish-grey: silt and clay.	Brown: almost entirely silt.

The vesicles of pumice grains are commonly infilled by mud, which is characteristically yellowish, with brown spots or patches: these colours are presumably due to the presence of limonite. Very similar material is sometimes found in the chambers of Foraminifera (Table 9).

Determinations of fossil microfauna have been made on mudstone fragments from Z 390 and Z 391. No fossil microfauna could be determined in B 150. Mr N. de B. Hornibrook (N.Z. Geological Survey) has kindly reported on the Foraminifera as follows:

"The sample of mudstone from Station Z 391 yielded the following fossil Foraminifera:

Hyperammina sp.
Cyclammina aff. *incisa* (Stache)
Bolivinopsis aff. *cubensis* (Cushman & Burmudez)
Textularia zeagglutta Finlay
Stilostomella paucistriata (Galloway & Morrey)
Dentalina soluta d'Orb.
Robulus sp.
Lagena marginata d'Orb.
Nodosaria longiscata d'Orb.
Eponides aff. *tenera* (Brady)
Pullenia two spp.
Cibicides tholus Finlay
Cibicides n. sp.
Cibicides aff. *collinsi* (Finlay)
Laticarinina halophora (Stache)
Globoquadrina primitiva Finlay
Globigerina sp.

This is a typical upper Wanstead microfauna (see *N.Z. geol. Surv. Bull. 46,* Dannevirke Subdivision). The association of *Bolivinopsis* aff. *cubensis, Globoquadrina primitiva* and *Cibicides tholus* in particular, indicates a Bortonian (Mid Eocene) age.

"The second sample, from Station Z 390, contained only a few fossil Foraminifera:

Involutina sp.
Haplophragmoides sp.
? *Karreriella bradyi* Cushman
Nodosaria longiscata d'Orb.
Cassidulina cf. *subglobosa* Brady
Eponides cf. *tenera* (Brady)
Globigerina aff. *turgida* Finlay

Table 9. Characteristics of Pumice and Foraminiferal Infillings in Sediments Associated with Lachlan Ridge

	Z 390	Z 391	B 150
Pumice	Pale yellowish-grey mud.	Predominantly pale yellowish-grey mud, with local brown spots and patches: occasionally brownish-yellow or greenish-yellow mud.	Pale yellowish-grey mud, with numerous brown spots and patches.
Foraminifera	Predominantly pale yellowish-grey mud: brown or yellowish-brown mud in a few specimens.	Predominantly pale yellowish-grey mud: brown or yellowish-brown in a few specimens.	Predominantly pale yellowish-grey mud, often containing brown spots and patches: greenish-brown or brown mud in a few specimens.

Although this microfauna is too poor for a close age determination, the assemblage is quite consistent with a Bortonian age."

FINER SEDIMENTS OF THE LACHLAN RIDGE

Apart from the three gravel dredgings, sediments from the Lachlan Ridge consist of sandy mud or muddy sand (Fig. 10); samples of these include both dredgings and cores. The largest particles in these sediments are actually small pebbles, which include shell fragments, pumice, sedimentary rock fragments, and plant fragments. These pebbles, when present, usually form a very minor proportion of the sediment, and rarely exceed 5 mm in diameter. There is, however, one sample of sandy mud (B 24) that contains occasional pebbles of greenish-grey calcareous mudstone up to 3 cm in diameter. These pebbles are angular, and most of them show a moderate degree of brown weathering. B 24 is a dredge sample, and probably represents a mechanical mixture of sandy mud and sandy gravel.

The mineralogy of the sand fraction is, for the most part, very similar to the sand fractions of the sand belt, mud belt, and central zone. Pumice, and in some samples shell and shell fragments, are the dominant types. Feldspar is moderately abundant, and quartz, semicrystalline rhyolite, granular rhyolitic tuff, greywacke fragments, and plant fragments are all present in subordinate amounts. Hypersthene is the most important accessory mineral. The normal types of aggregate, composed of material similar to the bulk of the sediment, are present but are much less common than in the mud belt or central zone.

Mudstone fragments, green aggregates, and brown aggregates are considerably more abundant than in the sand belt, mud belt, and central zone, although they still make up only a minor proportion of the sand fraction. These grain types may occur in surface samples or at any level in the cores. The mudstone fragments appear to have been originally greenish-grey, but many have been weathered to a reddish-brown or yellowish-brown colour. They show no striking differences with respect to the mudstone fragments in the Lachlan Ridge gravels, but they are too small to be positively identified. The green and brown aggregates, which are roughly equal in abundance, are very similar to those in the sand-belt salient, and are considered to be authigenic. The same glauconitic and limonitic chemotypes occur as in the salient, and the same morphotypes are found, together with certain additional varieties. Spheroids and ovoids (those derived from faecal pellets) are more abundant on the Lachlan Ridge than in the salient, but the subangular type (those derived from sedimentary rock fragments) still predominate. There are also composite masses that are clearly internal casts of Foraminifera, and partly rounded grains with one or two flattened surfaces that are evidently casts of single foraminiferal chambers. Transitional types of aggregate with an appearance intermediate between the green and brown varieties are found in some samples, but in others the two varieties are quite distinct.

Materials similar to those composing the green and brown aggregates are also found as infillings within pumice vesicles and foraminiferal chambers, although the green and brown materials occur in different relative proportions. The pumice vesicles often contain pale greenish-grey unconsolidated mud similar to that in the main bulk of the sediment, but this is sometimes replaced by compact green material similar to that forming the green aggregates. These vesicle infillings are clearly visible owing to the transparent nature of the glass. In the spheroidal vesicles the green material usually occupies the whole space, but in the elongated vesicles the green material may occupy only the centre of a vesicle and show a transition into normal mud at the two ends. Brown pumice infillings are less common than the green variety and are almost always composed of material similar to the glauconitic brown aggregates (chemotype 1). Infillings corresponding to the limonitic brown aggregates (chemotype 4) are very rare. The brown infillings have sharply defined borders, even in partly filled vesicles, and show no transition into normal mud.

Foraminiferal chambers frequently contain green or brown infillings, the brown variety being the more common. As in the corresponding pumice infillings, the brown material is almost always glauconitic (chemotype 1). The foraminiferal infillings are not clearly seen unless part of the shell has broken away. Partly broken Foraminifera with green or brown infillings are transitional into those varieties of green or brown aggregate that can be identified as foraminiferal casts.

Pumice and foraminiferal infillings composed of yellowish mud are also present. This material presumably owes its colour to limonite, although the limonite percentage must be considerably less than in the brown infillings. Yellowish pumice infillings are moderately common, but are normally less abundant than the green infillings. Yellowish foraminiferal infillings are rare, and are always subordinate to the green variety. Sample B 24 is exceptional, as it contains numerous yellow pumice infillings but comparatively few green pumice infillings. This upholds the view (see above) that this particular sample represents a mechanical mixture of sandy mud and sandy gravel.

No lamination is seen in the sandy mud or muddy sand of the Lachlan Ridge, although diffuse layering on a larger scale is sometimes present, individual bands being several centimetres or more thick. Organic burrows are the only visible small-scale structures.

DISCUSSION OF SEDIMENTARY REGIME

Factors Controlling the Deposition of Sediment

Off-shore sand belt (main part) and mud belt

There is no reason to doubt that sedimentation is taking place at the present day in the main part of the sand belt (excluding the salient) and in the mud belt, as their relations can be explained in terms of deposition under present-day conditions. The general transition from muddy sand to sandy mud away from the coast is evidently due to a corresponding decrease in the power of wave action. It is normally assumed that the various near-bottom currents grouped together as "wave action" become progressively weaker with depth and with increasing distance from the shore, and under these conditions any sediment actually being deposited on the sea bed should become progressively finer away from the shore. This generalisation appears to be true in areas where wave action is the main agent of transport, although the tendency is frequently reversed in parts of the shelf where tidal streams or oceanic currents predominate. The rate of progressive off-shore decrease in grain size cannot, of course, be applied in areas where sediments deposited at different times and under different conditions are exposed on the sea bed. For example, the relatively coarse sediment often found on the outer parts of continental shelves in many places passes shorewards into appreciably finer-grained sediment, but the coarse material in these areas was evidently deposited at an earlier and lower stand of sea level than the finer sediments nearer the shore. A systematic decrease in grain size away from the coast would not be expected in areas where tidal streams or oceanic currents predominate over wave action. Maximum tidal-stream velocities are normally some distance out to sea, and thus the effect of tidal streams (unlike wave action) shows an initial increase away from the shore. Again, the effects of oceanic currents tend to increase away from the coast. Tidal or oceanic currents thus do not account for the relationship of the sand belt to the mud belt.

The boundary between the main part of the sand belt and the mud belt is irregular in plan and varies considerably in depth. These irregularities are presumably due to local variations in the factors controlling sedimentation. In areas where the deposition of sediment is governed by wave action, the depth at which "sand" gives way to "mud" depends in a particular case on the intensity of wave action, and on the quantity and grade of sediments supplied by rivers and by coastal erosion. The transition from "sand" to "mud" will normally take the form of a gradual change from muddy sand to sandy mud, but a convenient ratio of sand to mud (such as 1:1) can be used to define the boundary. The depth of this boundary will vary from time to time and from place to place, since the supply, transport, and deposition of sediment depend on factors such as the local morphology of the sea bed, the height, frequency, and direction of waves, and the amount of sediment discharged by rivers in the vicinity. Local variations in these factors will often give rise to tongues projecting from the main belt of mud (or sand) into the main belt of sand (or mud). In some cases, there may even occur isolated patches of one sediment type surrounded by the other. If the local conditions producing them were only temporary, these tongues or patches would be transient and would tend to disappear when conditions returned to normal. Wave characteristics and river outflow are themselves governed by meteorological conditions, and temporary variations in wind or rainfall must cause corresponding variations in sedimentation. Thus a period of light winds would tend to allow the deposition of muddy sediment in shallower water than usual, since the power of wave action would be less than average: a period of heavy rain in the catchment of a river draining soft muddy country rocks would have a similar effect, as there would be a considerable temporary rise in the supply of fine-grained sediment.

The mud belt has evidently been deposited during the latest phase of sedimentation, and the underlying central-zone layer must therefore correspond to an earlier phase. This shows that the average rate of recent sedimentation in the mud belt must decrease progressively towards the central zone, falling to zero at the boundary. The central zone thus represents an area of present-day non-sedimentation. The simplest explanation is that in the region of the central zone, the near-bottom currents are slightly stronger than in the surrounding mud belt. The submarine morphology of the central zone gives no indication that wave action in that area would be exceptionally vigorous; the increased current strength is probably due to a weak tidal stream or to currents forming part of the general circulation of the bay. The central zone lies approximately half-way between the headlands of Cape Kidnappers and Mahia, with its long axis parallel to the long axis of the bay, and this symmetrical disposition indicates that the non-sedimentation zone is produced by currents governed by the overall morphology of the bay. Tidal streams or general circulation patterns would very probably show a symmetrical distribution with respect to the outlines of the bay, and Ridgway (1960) has shown by drift-card experiments that the surface water movements in the bay do show a distribution of this type. "The main inflow takes place approximately along the mid-line of the bay. This current bifurcates and the two currents thus formed follow the coast line and leave the bay at the northern and southern extremities" (Ridgway, 1960, p. 260). Although the pattern of surface-water movements and that of near-bottom currents do not necessarily correspond, it may well be significant that the region in which the surface flow lines are most concentrated (the region of inflow) passes over the central zone (see Fig.13). The concentration of flow lines indicates a local maximum of the rate of surface flow, and this is consistent with the presence in the same area of a velocity maximum in the near-bottom currents.

SAND-BELT SALIENT

This is considered here to be an area of non-deposition, for the following reasons:

(i) The widespread occurrence of green and brown aggregates containing authigenic glauconite. This mineral is generally found in areas of slow sedimentation (cf. Cloud, 1955, pp. 490–1), and this association is demonstrated in Hawke Bay by the occurrence of authigenic glauconite on

FIG. 13. Surface-current directions in Hawke Bay (after Ridgway, 1960). The 0 and 1 fathom isopachs on the main subsurface reflector are also shown. (Scinde Island forms the north-eastern part of Napier.)

the Lachlan Ridge, where the main subsurface reflector provides independent evidence of the slowness or absence of sedimentation (p. 46).

(ii) The anomalous location of the salient: it lies at a depth consistently greater than the part of the mud belt immediately to the south-west, and wave action must therefore be less intense. If wave action were the only significant sediment-transporting process in the area, sandy mud (similar to that in the mud belt) should be accumulating in the region of the salient. The absence of this sandy mud shows that in the salient, the bottom currents must be somewhat stronger than in the parts of the mud belt lying on either side. This effect cannot be explained in terms of wave action; it must be due to the presence of some other type of current, with its maximum velocity over the salient. Without more knowledge of the total flow pattern in the bay, the nature of this current cannot be determined with certainty. One possibility, however, may be suggested. The south-flowing surface current, which occurs off-shore from Napier (see Fig. 13), may be constricted and deflected by the pronounced irregularity of the coast at Scinde Island. This might give rise to a current stream flowing south-eastwards at an increased velocity, from a point north-east of Scinde Island. If the deeper water became involved in this movement, a zone of non-sedimentation might easily develop below the current stream.

The sediment of the salient does not belong to the present day, but it must have been deposited within the recent geological past. It probably corresponds to the sand belt of about 7,000 years ago, when sea level was approximately 5 fathoms lower than at present (Fairbridge, 1961, Fig. 14). This would account for the greater depth of the salient below present sea level (particularly at its southern end) as compared with the depth of the main sand belt in the same area.

OFF-SHORE GRAVEL ZONES

The coarse material in these zones cannot have been deposited under present-day conditions. The zones occupy the same depth range as the sand belt and the uppermost part of the mud belt, and there is no reason to suppose that wave action is locally so vigorous that gravel is being deposited rather than sand and mud, which occur at the same depth in other parts of the bay.

The nature of the gravels, and their location off the mouths of the Tukituki and Mohaka, can be most easily explained on the assumption that they represent accumulations of coarse fluvial sediment, brought down by the rivers during the late Pleistocene low stand of sea level. This coarse sediment would originally have been deposited along the lower parts of the river courses, probably in the form of flood plains, in the area that now corresponds to the upper part of the shelf. During the Flandrian rise in sea level, however, these fluvial gravels would have been reworked by the sea and converted into beach gravels.

The gravel zones have not been covered by the sand and mud forming at similar depths in other parts of the bay, and thus they present the appearance of non-sedimentation areas. Wave action would be more effective on a gravelly sea bed than over sand or mud, owing to an increase in near-bottom turbulence, and this effect must have played some part in preventing the deposition of fine sediment over the gravel zones. In addition the gravels as originally deposited along beaches would have been very porous, containing little or no fine-grained sediment. Any sand or mud subsequently deposited on top of the gravels would thus tend to percolate down through the spaces between pebbles and sink out of sight, leaving gravel exposed at the surface.

CENTRAL ZONE

The sediments of the central-zone layer clearly do not belong to the present day. The layer underlies the sediments of the mud belt, and probably ranges in age from about 9,000 years at the base to about 8,000 years at the top (see below); moreover the mechanical composition of the sediments forming the layer is not consistent with the pattern of present-day deposition.

The sand underlying the central-zone layer is very similar in lithology and faunal content to the sediments of the present-day sand belt, and was probably formed mainly by wave action at a depth of 20 fathoms or less. Deposition must have occurred at a time when sea level was relatively much lower than at present, the relative change in sea level being about 40 fathoms. Since the sand is about 10,000 years old, the change in sea level can be accounted for in terms of the general eustatic rise following the last Glacial period. There is no need to invoke a Flandrian tectonic subsidence in the centre of Hawke Bay to account for the level of the sand layer, although there was a great deal of subsidence in the region of Hawke Bay during the Tertiary and Pleistocene, and Flandrian uplift has taken place in some coastal areas.

Assuming that the sand below the central-zone layer corresponds to the "sand belt" of 10,000 years ago, it is probable that the mud belt and the underlying central zone are in turn underlain by a diachronous layer of sand, representing the progressive migration of the sand belt during the Flandrian eustatic rise in sea level. This diachronous sand layer would transgress across a surface consisting of pre-Flandrian sediments more or less levelled by marine erosion. The sand would not always, however, have the same lithology as the present-day sand belt. In particular, an exceptionally high proportion of mud and pebbles would have been present during the period of deposition of the central-zone layer.

The conditions under which the central-zone sediments were formed are less obvious than in the case of the underlying sand, since the assemblage includes types such as pebbly mud, which are not now being deposited in the area. The conditions of supply or transport must have been markedly different from those of the present day, but the sediments are clearly marine, as they contain numerous shells and shell fragments derived from marine organisms. They can, in fact, be explained in terms of wave action, as can the underlying sand and the overlying mud belt.

Assuming that these sediments were deposited during a time of rising sea level, the depth of deposition must have been slightly greater than that of the underlying sand. Taking a value of 10 fathoms for the latter gives 15–20 fathoms as a probable depth for the central-zone sediments. In plan, these would have formed a zone separating the sand belt of the period from the mud belt. Both the sand belt and the mud belt would have differed somewhat in mechanical composition from their present-day counterparts, owing to the unusual conditions of sediment supply and transport that prevailed at the time. This point will be discussed further at the end of this section.

The chief problem is the occurrence of relatively large clasts (pebbles) in the same sediment as relatively much finer material (mud). The pebbly mud layers must have been deposited by currents powerful enough to transport small pebbles but also saturated with fine-grained sediment, so that pebbles and mud were laid down together. This implies an exceptionally heavy supply of fine-grained sediment from the environment. The sudden increase in the proportion of mud at the base of the central-zone layer likewise indicates an increase in the supply of fine-grained sediment with respect to the sand below.

These effects can be explained in terms of the repeated changes of eustatic sea-level during the Quaternary. When sea level was at a relatively high stand, muddy sediments would be deposited on the shelf at depths below about 20 fathoms, except in areas where local current activity (particularly near the shelf edge) prevented deposition. During a subsequent fall of sea level these muddy sediments would be readily attacked by wave erosion, as they would for the most part be only a few thousand years old and relatively unconsolidated. Any coastal cliffs or platforms cut in such material, being soft and mechanically unstable, would be able to supply large quantities of mud to the sea. This would allow the deposition of very muddy sediments in relatively shallow water, as apparently happened in the case of some of the components of the central-zone layer. During a time of stationary or slowly changing sea level this effect would be lessened, as prolonged erosion at a given stand of sea level must tend to produce a beach of relatively coarse sediment, made up of sand, pebbles (if present), fossils, or concretions washed out of the muddy formation. This beach would "armour" the soft cliffs and protect them from erosion. When sea level was rising or falling rapidly, however, the shoreline would not be in any one place long enough for much coarse sediment to accumulate on the beach. The muddy sediments forming the cliffs and the foreshore would thus lie exposed to wave erosion.

It is therefore suggested that muddy sediments were deposited on the central part of the shelf at a time of relatively high sea level corresponding to the last pre-Flandrian interstadial. During the subsequent fall in sea level, and more especially during the still later rise at the beginning of the Flandrian, these earlier sediments suffered extensive wave erosion and supplied exceptional quantities of mud to the marine environment. The central-zone layer corresponds to deposition during the most rapid phase of the early Flandrian rise in sea level, while the underlying sand corresponds to an earlier and relatively static phase, when an armouring beach was formed and comparatively little mud was supplied to the sea.

The abundance of small pebbles in the central-zone sediments, as compared with their rarity in the underlying sand, is a fact requiring explanation. If the change from one sediment type to the other does in fact correspond to a slight rise in sea level, it might have been expected that the power of wave action would simultaneously decrease and that the maximum size of particles in the sediments would also decrease. The reverse situation is actually found, there being a conspicuous increase in the maximum size of rock particles. The sand contains shells and shell fragments with a maximum diameter equivalent to that of small pebbles, but this material is hydrodynamically equivalent to rock particles with a much smaller diameter.

The bottom-current components resulting directly from wave action presumably became weaker as sea level rose. On the other hand, additional effects that came into play at the same time as the rise in sea level may well have allowed the transportable size of particles to increase rather than decrease. For instance, the heavy influx of mud during the deposition of the central-zone sediments must have markedly strengthened the turbidity effect, that is the tendency for sediment-laden water to flow down any submarine gradient by virtue of its effective density relative to clear water. The actual magnitude of this effect may never have been very great, but it would certainly have provided an additional current component directed off-shore. Very muddy water would also tend to reduce the effective density of the pebbles, which would thus become more readily transportable.

The current strength necessary to move a sedimentary particle depends not only on its size but also on the nature of the underlying surface. It is quite possible that small pebbles would move over a sea-bed of muddy sand more readily than over relatively clean sand. Eddies tend to form around the base of pebbles, and on a clean sand bottom small depressions are formed, the pebbles subside into these, and transport becomes thereby more difficult. The adhesive quality of mud would tend to prevent the formation of these depressions, and in this respect transport over muddy sand would be easier than over clean sand. In addition, the presence of mud would help to reduce friction between the pebbles and the sea bed.

The heavy influx of mud during the deposition of the central-zone layer, together with the increased ease of pebble transport, must have had a considerable effect on the mechanical composition of the sand belt and mud belt of the period. The sand belt would have contained numerous muddy and pebbly layers, while the mud belt would have contained numerous layers in which small pebbles were relatively abundant.

LACHLAN RIDGE

The variable nature of the sediments associated with the Lachlan Ridge is a reflection of the irregular morphology of the ridge itself. Small banks, platforms, and depressions lie close together, and it is not surprising that local areas of sedimentation and non-sedimentation are both found, often within a short distance of one another.

The gravel samples presumably come from local areas where there is no present-day sedimentation. The three samples cover the depth range 50–70 fathoms, and probably represent near-shore sediments deposited during the latest low stand of sea level, at the end of the Pleistocene or the beginning of the Flandrian. These gravels have not been covered by later sedimentation, which indicates that in these areas the near-bottom currents are slightly stronger than in the immediate neighbourhood and thus prevent deposition of sediment. The gravel samples are all located near the crest of the ridge, and marine currents of all types would tend to be stronger there than on the nearby flanks.

The samples of sandy mud, which evidently comes from areas of deposition, are, except for the glauconite, very similar to the sandy mud being deposited in the mud belt. Rates of sedimentation must however be relatively low over most of the Lachlan Ridge, since the main sub-surface reflector rises rapidly on both sides of the ridge, and in places can actually be seen to converge with the sea bed. Furthermore, the reflector cannot be identified over the ridge itself. This evidence indicates that the reflector, as it reaches the ridge, passes into a feature that virtually coincides with the surface of the ridge and is overlain by a thin layer of more recent sediment which dwindles in places to nil and is never more than about 1 fathom in thickness. The deposition of sandy mud on the Lachlan Ridge can be explained in terms of wave action, but tidal and oceanic currents are probably more significant than over the mud belt, which is further from the edge of the shelf. The samples of muddy sand presumably come from areas of slow sedimentation, but the deposition of this material is difficult to explain in terms of transport by a single type of current. Sandy mud is evidently the normal variety of sediment being deposited at similar depths in other parts of the area. It is therefore suggested that the muddy sand represents sandy mud deposited by wave action, but subjected after deposition to the continual winnowing action of tidal or oceanic currents. These currents would be locally stronger than elsewhere, but not sufficiently strong to prevent sedimentation altogether.

Age of Central-zone Layer and Rates of Sedimentation in the Mud Belt

Of the five ^{14}C measurements made during the present work, only those from core B 21 are reliable indicators of the age of the sediment concerned. The consistency in the ages obtained from the two parts of core B 21, about 10,000 years, suggests that the amount of derived material is insignificant. If the samples from B 21 had contained an appreciable quantity of derived material, they would almost certainly have consisted of shells of different ages mixed together in different proportions, and the chances of the two ^{14}C dates being consistent would have been very small.

The results from core B 21 show that the sand underlying the central-zone layer is about 10,000 years old. The base of the layer itself must be slightly younger than this, probably about 9,000 years old. If the special characteristics of the central-zone sediments are in fact due to deposition during the most rapid phase of the early Flandrian rise in sea level, the top of the central-zone layer probably corresponds to the end of the rapid phase; that is, it probably corresponds in date to the slowing down of the rise in sea level. The latter came to a halt about 5,700 years ago (Fairbridge, 1961, Fig. 14) and the slowing-down process must have taken place somewhat earlier.

It has already been suggested that during the deposition of the central-zone layer, the sand belt of the period would have contained exceptional quantities of both pebbles and mud. The sediment of the sand-belt salient, which probably represents the sand belt of about 7,000 years ago, contains a high proportion of mud but no significant quantities of pebbles. It is probable, therefore, that the sediments of the salient are younger than any part of the central-zone layer, and if so, the top of the layer must be more than 7,000 years old. For the sake of convenience, an age of 8,000 years will be assumed. Thus the central-zone layer probably ranges in age from about 9,000 years at the base to about 8,000 years at the top.

The average rate of sedimentation over much of the mud belt can be calculated from the depth of the central-zone layer below the sea bed, assuming that the top of the layer corresponds to a date of about 8,000 years B.P. The rate R, in millimetres per year, will be given by $R = 0{\cdot}23\ H_m$, where H_m is the depth in fathoms of the layer. Thus the greatest average rate, found at the southern end of the mud belt where $H_m = 10$, is $R = 10 \times 0{\cdot}23 = 2{\cdot}3$ mm per year. A commoner value, with $H_m = 3$, will be $R = 0{\cdot}69$ mm per year.

The ^{14}C date of 2,030 years determined on carbonised wood from Station B 4 cannot be relied upon as an age indicator for the enclosing sediment, since there is no guarantee that the wood was not partly or wholly derived from older sediments. The two dates from core B 23 are also unusable; the difference between the carbonate date (15,000 years) and the organic-carbon date (8,600 years) shows that derived material is definitely present in the carbonate fraction, and probably also in the organic-carbon fraction.

PROVENANCE

Most of the pebbles and sand grains are derived either from the Taupo volcanic sequence (Quaternary) or from the greywacke sequence (Mesozoic). Only a small quantity are derived from Tertiary sedimentary formations, and nearly all of these Tertiary fragments occur in the Lachlan Ridge area (Table 7). The various types of grain attributable to these three sources are listed in Table 10.

large quantities of Taupo ash that have evidently been transported to Hawke Bay and deposited there. Although the main eruptive centres were near Taupo (about 60 miles to the north-west of Hawke Bay), material from the stronger eruptions spread over a wide area, with the result that some Taupo ash layers can be followed outwards in the subsoil as far as the coast of Hawke's Bay (Grange, 1931, p. 231). All the rivers draining into the northern part of the bay cut through the area covered by Taupo ash, and the headwaters of the Mohaka in particular extend north-westwards into areas where the Taupo ash beds are several feet thick. The great bulk of rhyolitic ash in Hawke Bay is represented by the greenish-grey pumice with adhering mud, and this no doubt corresponds to pumice washed off the hills and down to the sea by streams and rivers, and thence transported across the sea bed by marine currents. The white mud-free pumice, which is far less common, probably corresponds to ash falling directly into the sea from a volcanic cloud during an eruption, or else transported in a floating condition by rivers during or shortly after an eruption.

Table 10. Sources of Hawke Bay Sediments

Taupo Sequence	Greywacke Sequence	Tertiary
Glassy rhyolitic pumice and rhyolitic glass	Greywacke	Mudstone
Semicrystalline rhyolite	Argillite	Sandstone
Rhyolitic tuff	Greenish quartz	(Mica ?)
Colourless feldspar	Yellowish quartz	
Most of the colourless quartz, including all those grains with well developed crystal faces	Yellowish feldspar	
Hypersthene	Some colourless quartz	
Augite	(Mica ?)	
Hornblende		
Magnetite		
(Dark glass and pumice ?)		

The various types of rhyolitic pumice, although they vary greatly in vesicularity, can all be matched more or less closely with types that are abundant in various members of the Taupo sequence. The semicrystalline rhyolite and rhyolitic tuff are very similar to types present as inclusions in some Taupo ash layers, although they never form more than a small proportion of the ash. The colourless feldspar, hypersthene, and magnetite are undoubtedly phenocrysts, derived from the Taupo sequence, as they are frequently euhedral and sometimes have rhyolitic pumice adhering to them: they can also be matched with phenocrysts in the Taupo sequence. The augite, hornblende, and pyramidal quartz are again almost certainly derived from the Taupo sequence, although they have not been observed adhering to pumice: their euhedral shape indicates that they are volcanic phenocrysts, and they can be matched with phenocrysts in the Taupo sequence. The dark glass and pumice may be derived from the Taupo sequence, as similar material is a minor constituent in some Taupo ash layers; but other sources such as the more basic volcanoes of the Bay of Plenty are possible.

There is no difficulty in accounting for the

The greywacke and subordinate argillite fragments correspond closely to types that are widespread in the Mesozoic greywacke formation of the central North Island ranges. Greenish and yellowish quartz grains similar to those found as individual fragments are commonly present in greywacke pebbles. Some of the colourless quartz grains may represent greenish or yellowish grains from the greywacke, with the green (chloritic) or yellow (ferruginous) material removed by abrasion. The occasional yellow feldspars are allocated to the greywacke sequence, since yellow weathering is common in the greywacke fragments but very rare in fragments belonging to the Taupo volcanic assemblage. The transport of the greywacke and argillite to Hawke Bay presents no difficulty, as the headwaters of the Mohaka flow for miles over greywacke country.

Some of the mudstone and sandstone fragments on the Lachlan Ridge are shown to be Tertiary by microfaunal evidence, and the remaining fragments of this type on the Lachlan Ridge and those in the central zone are probably also Tertiary (or Lower Quaternary). The general lack of Tertiary or Lower Quaternary fragments in Hawke Bay (except over the Lachlan Ridge) show that in spite of the large coastal area underlain by formations of this age, very few fragments survived the process of transport down the rivers and into the marine environment. This is consistent with the relatively low mechanical strength and hardness of the Tertiary and Lower Quaternary formations. The mechanical strength of the rhyolitic pumice is also relatively low, but in this case wastage during transport was heavily outweighed by the very large quantities of ash supplied to the environment during the period of the Taupo eruptions.

The relative abundance of angular Tertiary rock fragments on the Lachlan Ridge, particularly in the gravel dredgings, shows that the ridge must consist, for the most part, of Tertiary rocks, apart from a thin covering of recent sediment. Greywacke fragments are only a very minor constituent of the gravels and it is thus very unlikely that Mesozoic-type greywackes form a significant part of the ridge.

Two main sources are apparent for the silt and clay fractions in the sediments of Hawke Bay. These are (i) the soft Tertiary and Lower Quaternary mudstone formations, which are widespread in the area surrounding the bay, and (ii) the soil and subsoil of the area surrounding the bay, which contain (in addition to other materials) silt and clay representing volcanic ash (weathered and unweathered), loess, and weathered bedrock. Clay mineral determinations at present available are not sufficiently numerous to determine the relative contributions of these two sources. Greywacke and argillite, because of their high mechanical strength, can only have been a relatively unimportant source of silt and clay.

AUTHIGENIC MINERALS

GLAUCONITE

The main development of authigenic glauconite is in the sandy mud and muddy sand of the Lachlan Ridge, where it occurs in green aggregates, pumice infillings, foraminiferal infillings, and in most of the brown aggregates. Smaller quantities of authigenic glauconite are found in the sand-belt salient: the mineral is present in the green aggregates and many of the brown aggregates, but is rare in pumice infillings, and is absent from foraminiferal infillings. Rare glauconitic pumice infillings, presumably authigenic, are present in the uppermost part of the central-zone layer (Table 11). As previously mentioned, green and brown aggregates are found in the parts of the mud belt flanking the salient. The conditions giving rise to the formation of these aggregates in the salient may extend for a short distance into the mud belt. Alternatively, the green and brown aggregates may have been transported by currents from the salient to the mud belt. Whichever is the case, the deductions made here regarding the origin of the green and brown aggregates in the salient will apply, with little modification, to the corresponding aggregates in the adjacent parts of the mud belt.

Cloud (1955, p. 484) summarised the different forms in which glauconite may occur. Two of the commonest forms are represented in Hawke Bay by the green and brown aggregates and the foraminiferal infillings. Glauconitic pumice infillings are not mentioned by Cloud (1955) and probably exist only in a few areas. Pumice infillings of this type are found in the sediments of the Chatham Rise, along with other forms of glauconite (Norris, 1964). Although a comprehensive discussion on the origin of glauconite is not appropriate in the present account, the nature and distribution of the glauconite aggregates and infillings permit some conclusions to be drawn regarding the conditions under which glauconite is formed in these particular localities.

(i) The presence of glauconite in the uppermost parts of cores and in surface samples shows that the formation of the mineral has continued up to the present day. The glauconite must also have formed very rapidly (from the geological standpoint) and a maximum age limit is given by its occurrence as infillings inside Taupo pumice vesicles, the pumice being Upper Pleistocene to Recent in age.

(ii) The glauconite must have developed in local chemical micro-environments. This is most obvious with regard to pumice vesicles and foraminiferal chambers, where the micro-environments would be provided by mechanical occlusion. The spheroidal or ovoidal green (and brown) aggregates are interpreted here as altered faecal pellets, and in this case micro-environments could exist in the interstices between the inorganic particles. It would tend

Table 11. Distribution of Micro-environments Containing Authigenic Glauconite and Primary Authigenic Limonite.

Area	*Aggregates (derived from faecal pellets)*	*Aggregates (derived from sedimentary rock fragments)*	*Pumice Infillings*	*Foraminiferal Infillings*
		a. Authigenic Glauconite		
Sand-belt salient	Moderately common	Common	Rare	—
Central zone	—	—	Rare	—
Lachlan Ridge (sandy mud and muddy sand)	Common	Very common	Moderately common	Common
Lachlan Ridge (gravels)	—	—	—	—
		b. Primary Authigenic Limonite		
Sand-belt salient	—	—	—	—
Central zone	—	—	Moderately common	—
Lachlan Ridge (sandy mud and muddy sand)	—	—	Moderately common	Rare
Lachlan Ridge (gravels)	—	(None identified)	Moderately common	Moderately common

to arise as a result of the high concentration of organic matter that occurs in faecal pellets, and would be protected by a greater degree of compaction of the pellets as compared with the surrounding sediments. The subangular green and brown aggregates are interpreted here as altered sedimentary rock fragments. Micro-environments could arise in any such fragments containing a certain amount of pore space, particularly if the rock also contained organic material. The age of the fragments concerned has not been determined accurately, but they have the appearance of Tertiary and Lower Quaternary sedimentary rocks.

(iii) There has been a marked accumulation of iron within the glauconitic material.

(iv) The Lachlan Ridge can be shown, by reference to the sub-surface reflector, to be an area where sedimentation is slow or absent. Glauconite normally occurs in areas of slow sedimentation (cf. Cloud, 1955, pp. 490–1), and the presence of the mineral on the Lachlan Ridge is consistent with this general observation. The presence of glauconite in the sand-belt salient indicates that the latter is also an area where sedimentation is slow or absent, but independent evidence is lacking in this case.

Both ferrous and ferric iron are essential in the glauconite formula (Burst, 1958, Tables 2 and 3) and the conditions for its formation must therefore include a range of Eh (redox potential) in which both states of iron are present in significant amounts. This will be called here the "intermediate" range of Eh. Under highly oxidising conditions, nearly all the iron in a sediment will be in the ferric state, occurring as hydrated ferric oxide or Fe_2O_3-bearing clay minerals. Under highly reducing conditions, on the other hand, nearly all the iron will be in the ferrous state, being taken up either in FeO-bearing clay minerals or in ferrous sulphides. It is thus clear that a too high or too low Eh will prevent the development of glauconite, which can be stable only within the intermediate range of Eh (compare Burst, 1958, p. 482; Hower, 1961, p. 323). Conditions in marine sediments vary from highly oxidising (red clays) to highly reducing (black sulphide-bearing muds), and it is therefore probable that the range of Eh necessary for the development of glauconite is fairly common. Furthermore, marine sediments with a suitable Eh will usually contain all the chemical ingredients required for the development of glauconite (ferric oxide, potash, silica, alumina, and magnesia). Many of these sediments will therefore be glauconitic.

It does not follow, however, that all glauconitic sediments will contain the mineral in a relatively pure and concentrated form. The glauconite always carries a much higher percentage of iron than the remainder of the sediment, and most of the iron in the glauconite must therefore be derived from pre-existing iron compounds, which decomposed during the process of glauconitisation. The distribution of glauconite in a sediment will thus be controlled by the distribution of the iron taken up during glauconitisation. If this iron is uniformly distributed through the sediment, the glauconite will also be uniformly distributed. Under these conditions, the glauconite will be masked, being held in solid solution with other clay minerals or dispersed through the sediment in the form of minute particles. No pure glauconite will be visible, although the sediment may acquire a noticeably green colour.

The small masses of relatively pure glauconite that occur in Hawke Bay (as well as in many other areas) must therefore have developed from local concentrations of iron. In some localities these concentrations take the form of clastic grains of iron-bearing minerals (compare Galliher, 1939), but there is no evidence that the iron in the Hawke Bay glauconite is derived, either directly or indirectly, from clastic minerals. The clastic iron-bearing minerals in the sediments of Hawke Bay rarely show any sign of alteration, and these minerals are present in far too small amounts to supply the iron needed for glauconitisation. In some cases glauconite could develop from derived limonite in sedimentary rock fragments, but this would provide no explanation for the glauconite in other types of micro-environment. It is therefore considered here that the iron that has accumulated in the Hawke Bay glauconite is derived from sea water.

The following mechanism is suggested. Virtually all the iron in sea water is in the ferric state, almost all of it being in two chemical forms, ferric hydroxide and ferric phosphate (Cooper, 1948a, pp. 300–1). These compounds are almost entirely in the colloidal state (Cooper, 1948b, p. 315) and it is found that significant proportions of the colloidal micelles are adsorbed on organic colloids and larger particles of organic material (Cooper, 1948a, pp. 300–1). This leads to the possibility that an organism, by capturing the organic particles in question and digesting the organic matter but rejecting the iron, could progressively concentrate iron compounds in its immediate neighbourhood. A process of this type has been suggested by Hedley (1960, p. 291) to account for the presence of iron in the shell of the foraminifer *Gromia oviformis,* and bacteria living in a sedimentary environment could probably behave in a similar way.

The organic material available to bacteria within a sediment may be divided into three categories:

(i) Terrigenous organic material: in Hawke Bay, this consists mainly of plant fragments.

(ii) Autochthonous organic material. This includes the tissues, secretions and excretions of the benthic fauna, and the tissues of dead plankton and nekton.

(iii) Vagrant organic material in the sea water, carried as particles in suspension, in colloidal solution, or in true solution. Particles of this type, as already stated, carry much of the iron in sea water.

Under conditions giving rise to a low concentration of terrigenous and autochthonous organic material in the sediments, the bacterial flora might be forced to retreat into various protected micro-environments. The bacteria might also be forced to ingest a larger proportion of vagrant organic matter than usual. These processes in combination would cause a progressive concentration of iron compounds in the micro-environments. A similar process has been suggested by Norris (1964).

The iron will initially be in the form of ferric compounds (hydroxide and phosphate) and will remain in the ferric state if the Eh is sufficiently high. With an Eh in the intermediate range, however, the iron would be partly reduced to the ferrous state and conditions would become suitable for the formation of glauconite. The ferric-hydroxide component would be reduced to a mixture of iron oxides, and these could produce glauconite either by combining directly with dissolved potash and silica in the sea water, or by reacting with an aluminous detrital illite to give glauconite plus colloidal aluminium hydroxide. Similar reactions could take place in the case of the ferric phosphate, but here it would be necessary to suppose that the phosphate component was released in solution. The development of glauconite in this manner will take place mainly within the uppermost few inches of sediment, where most of the bacteria living in sediments are located. Bacteria are also considered here to play an essential part in the formation of primary authigenic limonite (see below), whose development will also be mainly confined to the uppermost few inches of sediment. Slow deposition will thus favour the formation of glauconite and primary authigenic limonite, since rapid deposition will bury individual micro-environments too quickly and they would not remain within the superficial, highly bacterial layer.

The essential requirement for the appearance of glauconitic micro-environments, besides an appropriate Eh and a slow rate of deposition, thus seems to be a low concentration of terrigenous and autochthonous organic material within the sediment. Conditions on banks and other areas of slow sedimentation would fulfil this requirement. The terrigenous organic fraction is transported in the same way as the inorganic sediment fraction, and other things being equal, areas of slow total sedimentation would be areas with a low rate of supply of terrigenous organic matter. In addition, the bottom currents in areas of slow sedimentation are characteristically more vigorous than in the surrounding regions, and the more fluid autochthonous organic matter (e.g. slime trails and some types of faecal material) would tend to be washed out and dispersed in the sea water. Both the slow sedimentation and the vigorous bottom currents would thus tend to reduce the total concentration of terrigenous and autochthonous organic matter in the sediment.

The mechanical removal of organic matter would tend to raise the value of Eh within the sediment, and it is possible that the combination of a low concentration of organic matter and an intermediate Eh is only found when the sea-water mass overlying the area possesses a relatively low oxygen content. A layer of oxygen-poor water extending from roughly 50 to 500 fathoms is commonly found in the open sea (Harvey, 1955, pp. 32–3), and this range does correspond approximately with the depth zone in which present-day glauconite is found.

Although currents may be instrumental in creating micro-environments by removing organic material from the bulk of the sediment, too high a current velocity would tend to destroy them. Organic material would be washed out of the micro-environments themselves, and the inorganic structures containing the micro-environments would suffer progressive mechanical disintegration. Micro-environments would also be destroyed by a very low total rate of supply of terrigenous and autochthonous organic matter, since the bacteria within them would be starved by the general lack of nutrient.

Limonite

This mineral is present in three different forms:

(i) Primary authigenic limonite, formed by precipitation in place. This occurs in the yellowish pumice and foraminiferal infillings present in the Lachlan Ridge gravels, in the finer sediments of the Ridge, and also in the yellowish pumice infillings near the surface of the central-zone layer (Table 11). The sporadic yellow pumice infillings in the mud belt have probably been transported by currents from the central zone or the Lachlan Ridge gravels, where infillings of this type are relatively common. If this is correct, the limonite in these infillings would strictly come into the category of derived limonite.

(ii) Secondary authigenic limonite, formed by the oxidation of glauconite. This is found in brown aggregates, and in pumice and foraminiferal infillings composed of material similar to the brown aggregates. The limonite in brown aggregates belonging to chemotypes 1 and 2 is probably all secondary authigenic, and this also applies to the limonite in the outer zone of those belonging to chemotype 3. However, the limonite in the core of chemotype-3 brown aggregates is probably derived (see below). Two varieties of chemotype-4 brown aggregates are possible, one variety containing secondary authigenic limonite throughout, and the other containing secondary authigenic limonite in the outer zone and derived limonite in the core: both of these varieties are probably present. The material interpreted here as containing secondary authigenic limonite is normally associated with glauconite, and is much darker in colour and more compact than the material containing primary authigenic limonite.

(iii) Derived limonite, formed by subaerial or submarine weathering prior to the deposition of the sediment. This is most noticeable in the brown-weathered sedimentary rock fragments of the Lachlan Ridge but is also to be found in many of the greywacke fragments that are present throughout most of the sediments of the bay. In addition, derived limonite is found in the cores of chemotype-2 green aggregates and chemotype-3 brown aggregates: these particular aggregates are evidently brown-weathered sedimentary rock fragments which have only been partly glauconitised. Derived limonite probably also occurs in the cores of some chemotype-4 brown aggregates.

The primary authigenic limonite is considered to represent iron concentrated in the same way as the iron in the glauconite: that is by the bacterial capture of organic particles with adsorbed iron compounds, the bacteria being located in suitable micro-environments. The Eh in these particular micro-environments was evidently too high for glauconite to exist, and all of the iron was forced to remain in the ferric state. The adsorbed ferric hydroxide could simply have precipitated as limonite, but the ferric phosphate must have decomposed with the deposition of additional ferric hydroxide and the loss of the phosphate component in solution.

No primary authigenic limonite has been identified in faecal pellets or in sedimentary rock fragments. It is possible that in these micro-environments Eh is always sufficiently low to cause glauconite rather than limonite to develop. Other factors, however, must also be taken into account. With faecal pellets, the relatively high Eh associated with limonite might cause decomposition of the organic matrix, this being followed by the disintegration of the pellets. In sedimentary rock fragments, primary authigenic limonite would be very difficult to distinguish from derived limonite.

Summary of Factors Controlling Formation of Glauconite and Primary Authigenic Limonite

The views expressed here on the conditions of glauconite and limonite formation are summarised in Fig. 14, which also shows the probable fields occupied by the sand belt, mud belt, central zone and Lachlan Ridge. These diagrams make the following assumptions:

(i) An increase in bottom-current velocity or a decrease in the rate of supply of terrigenous or autochthonous organic material will tend to generate micro-environments. These tendencies are simultaneously expressed by boundary X in Fig. 17. The position of this boundary may vary according to the type of micro-environment and may also vary within a particular type of micro-environment. For the purpose of discussion and illustration, however, it will generally be convenient to use a boundary representing the average position of X, and this is done in Fig. 14.

(ii) An excessive increase in current velocity or an excessive decrease in the supply rate of terrigenous or autochthonous organic material will tend to destroy micro-environments. These tendencies are expressed by boundary Y in Fig. 14. The position of boundary Y may also vary according to the nature of the micro-environment, and a boundary representing the average position of Y will likewise be used.

(iii) An increase in current velocity or a decrease in the supply rate of terrigenous or

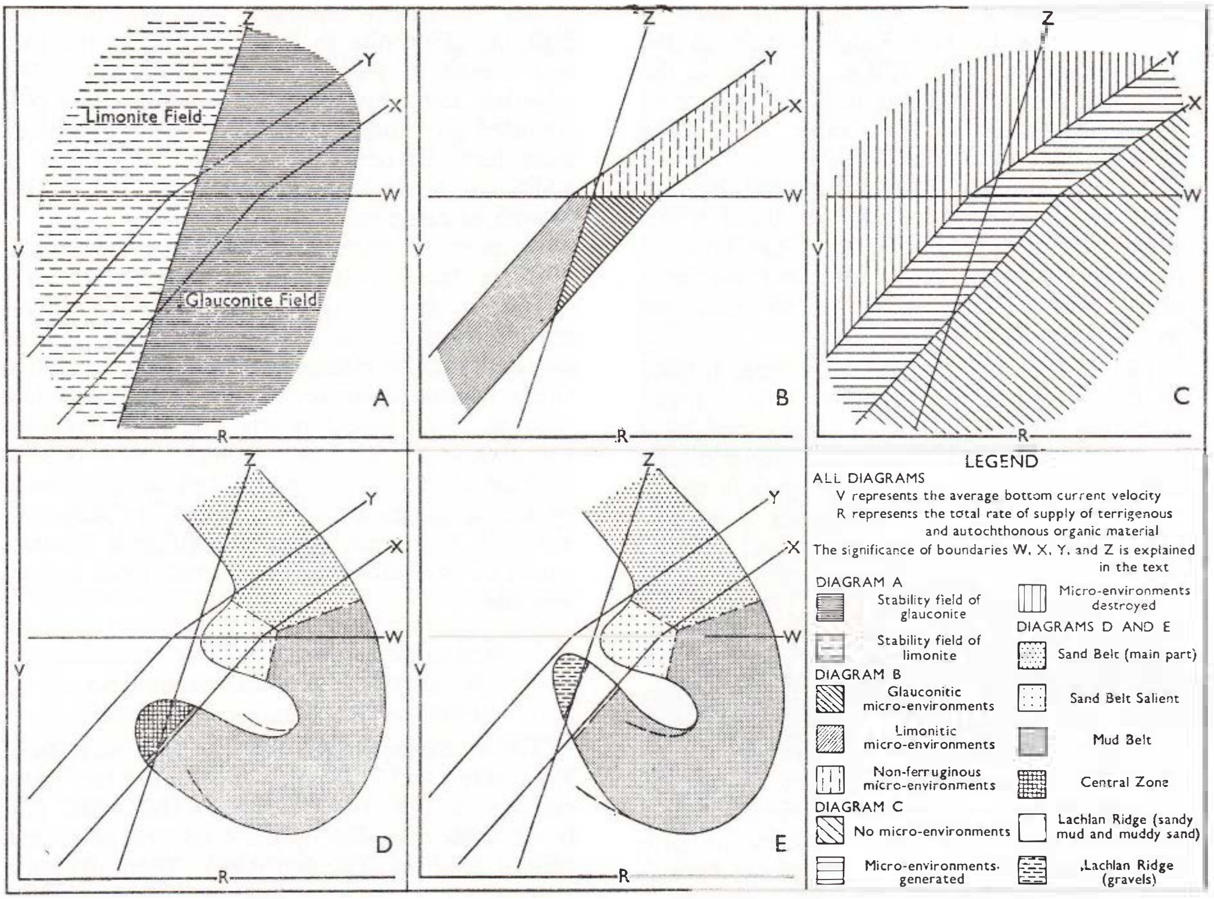


FIG. 14. Diagram showing conditions for the formation of authigenic glauconite and primary authigenic limonite.

autochthonous organic material will cause the general Eh in the sediment to rise.

(iv) When Eh in a particular micro-environment rises above a certain value, limonite rather than glauconite will be formed.

(v) The slope of the glauconite-limonite boundary (Z, Fig. 14) is such that glauconite would tend to occur with a high current velocity and a high rate of supply of terrigenous and autochthonous organic material, while limonite would tend to occur with a low current velocity and a low rate of supply of this organic material.

(vi) The general Eh in the sediment, and hence the position of boundary Z, will vary according to the oxygen content of the overlying sea water. An increase in the oxygen content will cause boundary Z to move to the right, while a decrease will cause the boundary to move to the left.

(vii) The capture of vagrant iron-bearing particles, and thus the formation of glauconite and limonite, would be inhibted by high current velocities, which would tend to keep the particles in suspension. This effect is expressed by boundary W in Fig. 14. Micro-environments could still exist on the high-velocity side of this boundary, but they would not concentrate iron, and the bacteria within them would have to subsist on terrigenous and autochthonous organic matter and on dissolved nutrients. Since this effect reduces the total supply of available nutrients in the sediment, the conditions expressed by boundaries X and Y will be encountered further along the R ordinate (see Fig. 14) than would otherwise be the case. Boundaries X and Y are therefore deflected in the appropriate direction where they cross boundary W.

(viii) The total rate of supply of terrigenous and autochthonous organic material is lower in the sand-belt salient, in the central zone, and on the Lachlan Ridge than in the mud belt.

The rate of supply is also lower in the main part of the sand belt than in the mud belt.

Whether glauconite or limonite appears in a particular micro-environment depends on the Eh of that micro-environment. There must be some variation from one to another, even within a limited area, and this is shown most clearly by the pumice infillings in the finer sediments of the Lachlan Ridge, where both glauconite and primary authigenic limonite are present in significant quantities. Eh will also vary to some extent from one type of micro-environment to another, and this is again shown by the finer sediments of the Lachlan Ridge, where the ratio of primary authigenic limonite to glauconite is higher for pumice infillings than for foraminiferal infillings. The prevailing Eh of different areas can, however, be compared on the basis of the relative abundance of glauconite and primary authigenic limonite. Table 11 summarises the distribution of these minerals, and the data show that Eh is highest in the Lachlan Ridge gravels, somewhat lower in the central zone, lower still in the finer sediments of the ridge, and lowest in the sand-belt salient. The occurrence of secondary authigenic limonite shows that in some micro-environments, Eh tends to rise over a period of time. This effect is probably due to the progressive dissipation of organic matter.

The conditions under which the different types of micro-environment can develop, or whether they can develop at all, depend on a number of variable factors. These include:

- The porosity and organic content of faecal pellets.
- The porosity and organic content of pumice and foraminiferal infillings.
- The porosity and organic content of sedimentary rock fragments.
- The size and shape of pumice vesicles.
- The species of Foraminifera.
- The dissolved nutrient concentration in the overlying sea water.

These factors will generally change from one area to another, and changes of this type are no doubt responsible for the observed variations in the relative abundance of the different types of micro-environment. For instance, the absence of foraminiferal micro-environments from the sand-belt salient and from the central zone may be due to the washing-out of fine clay particles from the mud filling the chambers, the result being a porosity too great for micro-environments to develop. This suggestion is consistent with the lack of sedimentation in the salient and the central zone. On the other hand, the Lachlan Ridge gravels also correspond to local areas of non-sedimentation, but these gravels do contain foraminiferal micro-environments: the washing-out effect must in this case be overcome by some other factor, possibly a high concentration of dissolved nutrients.

No micro-environments have been detected among the sedimentary rock fragments in the Lachlan Ridge gravels. This may be due to a lack of sufficient pore space. On the other hand, the very similar fragments in the finer sediments of the ridge frequently contain micro-environments. Most of the fragments in the gravels are calcareous, and it is therefore possible that in the finer sediments additional pore space is created by the removal of similar calcareous material in solution. The occurrence of numerous well-formed internal casts of Foraminifera in the finer sediments of the ridge shows that, in these sediments, there is in fact a tendency for $CaCO_3$ to dissolve.

INTERNAL STRUCTURES IN THE SEDIMENTS

The internal structures in the sediments fall into two categories: stratification and organic structures. Stratification includes both "lamination" with layers up to a few millimetres in thickness, and "banding" with layers up to several centimetres in thickness. The organic structures include aggregates (normal types) and organic burrows.

LAMINATION

This has been found only at four localities in the mud belt (cores B 124, B 132A-B, B 22 and B 145) and at two in the central zone (cores B 125 and B 127). In other parts of the bay, no lamination is visible; but organic structures are very abundant, and organic disturbance has evidently been too severe for lamination to survive.

Since wave action is a variable function, depending mainly on the distribution of wind direction and velocity in time and place, sediments deposited by this process should exhibit lamination on a scale corresponding to the time variation of wave action in the area (unless the lamination were destroyed by organic activity). Other things being equal, the coarser bands would correspond to periods of high winds and strong wave action, and the finer bands to periods of less powerful winds and weaker wave action. The strength of wave action in Hawke Bay will be affected by the distribution and variation of wind velocities and directions over the whole area of the south-west Pacific. Wind fluctuations on a time-scale of a few hours or less will have no significant effect on wave action, as the response of waves to wind is very sluggish over a short period. With a time-scale of several days, on the other hand, fluctuations in wind velocity will give rise to closely correlated variations in the strength of wave action, and it might be expected that the sediments would exhibit laminations corresponding to the successive passage of anticyclones and depressions over the New Zealand area. Variations in the quantity and grain size of the detritus supplied to the bay by rivers and coastal erosion will also tend to produce lamination, but these variations are controlled by factors such as river discharge and breaker height, which are themselves correlated with the passage of anticyclones and depressions.

The probable scale of anticyclone-depression lamination can be calculated for the area in which the main sub-surface reflector is discernible. Anticyclones pass over the New Zealand region at an approximate rate of one every 6 to 10 days, or about 45 per year (Garnier, 1958, pp. 18, 37). Average rates of sedimentation reckoned from this reflector vary from about 2·3 mm per year down to nil. On the probable assumption that recent rates of sedimentation do not differ widely from these average rates, the mean thickness of the potential laminae will vary from about 0·05 mm down to nil. Such lamination will frequently not be discernible, since thicknesses of this order are only of the same order as the coarser sediment fractions. However, the thickness of the laminae will vary with the intensity of the depressions, and exceptionally severe depressions might easily give rise to visible lamination in the 0·1–1·0 mm range, particularly in localities with high sedimentation rates. No lamination as fine as this has been observed in the area of the main sub-surface reflector, but the lamination in the 0·1–0·5 mm range, seen in cores B 124 and B 132B from the mud belt and in cores B 125 and B 127 from the central zone, is almost certainly due to the alternation of anticyclones and depressions. It is probable that only the more intense weather fluctuations are represented, as the weaker fluctuations would not produce laminae of discernible thickness.

The larger-scale lamination in the 1–6 mm range, visible in cores B 124, B 132A, B 132B, B 125 and B 127, is obviously much too coarse for anticyclone-depression lamination, and there can be little doubt that it corresponds to an annual rhythm. Although meteorological fluctuations involving time intervals of several years or decades undoubtedly take place in the New Zealand area (cf. de Lisle, 1961), there appears to be no well developed rhythm with a period longer than 1 year.

Rainfall in the area surrounding Hawke Bay shows an annual periodicity: the maximum rainfall occurs during the autumn (in the north) or winter (in the south), while the minimum occurs during the spring (Garnier, 1958, Fig. 9). Evapotranspiration must also show an annual periodicity, since the process becomes more rapid with increasing temperature (Thornthwaite, 1945, p. 686) and will therefore reach a maximum during the summer. Annual variations in rainfall and evapotranspiration will thus cause river discharge to reach a maximum during the autumn and winter and a minimum during the spring and summer. The rate at which the rivers in the area supply sediment to the sea will therefore reach a maximum during the autumn and winter. This maximum rate of supply will cover both the sand and mud components of the fluvial sediment. The rate of supply of sand will have little effect on the rate at which sand is transported away from the coast by wave action, since material of this grain size settles out rapidly and any excess will merely cause local aggradation of the sand belt. The mud component, however, may stay in suspension for a considerable time after reaching the sea: an increase in the fluvial supply of mud will therefore cause the sea to become muddier, and this in turn will produce an increase in the proportion of mud in the sediments being deposited on the sea bed. Thus the relatively muddy layers in lamination of the 1–6 mm type probably represent deposition during the autumn and winter, while the relatively sandy layers represent deposition during the spring and summer.

Annual lamination could also arise from a rhythmic annual variation in regional wind velocity. Periods of strong winds and vigorous wave action would produce relatively coarse laminae, while periods of weaker winds and less vigorous wave action would produce relatively fine-grained laminae. However, no such annual periodicity in wind velocity has yet been demonstrated.

On the assumption that the lamination in the 1–6 mm range corresponds to an annual rhythm, the rates of deposition in the sediments containing this type of lamination must lie between 1 and 6 mm per year. It is not possible, however, to compare rates of sedimentation calculated in this way with rates calculated from the depth of the central-zone layer, since B 124 and B 132A-B lie outside the area where the depth of the layer is known, while B 125 and B 127 belong to the central-zone layer itself.

The lamination in the sharply defined band near the top of cores B 22 and B 145 has apparently originated in a quite different way from the two types of lamination already discussed, and is dealt with below.

Banding

The larger-scale type of stratification shows little or no evidence of periodicity, and the individual units nearly always grade into one another, without sharp contact. These units represent decades and centuries, time intervals that can be readily explained on the basis of long-period fluctuations of climate. The nature of the sediment being deposited during any phase would depend on rainfall, wind velocity, and (in the case of the Taupo ash) the frequency of volcanic eruptions. The banding cannot be explained by eustatic or tectonic changes in sea level, as these changes would require thousands rather than hundreds of years to achieve sufficient amplitude to cause significant changes in sedimentation, except along the edges of the bay.

The sharply defined banding in cores B 132A and B 132B cannot, however, be explained in terms of meteorological fluctuations. Rainfall and wind velocity never show an abrupt change from one more or less steady level to another, and in any case the type of banding in these cores is quite exceptional for Hawke Bay. Evidently some localised factor is involved that does not operate in other parts of the bay. The banding can be interpreted on the assumption that the muddy layers represent material deposited during phases of hyperpycnal* outflow at the mouth of the Nuhaka River. No measurements of sediment content are available for this river, but the rocks in the catchment area consist of Tertiary formations with a high proportion of soft argillaceous beds, some of which are bentonitic. The Waipaoa River, which drains similar country north of Gisborne and enters the sea in Poverty Bay, has a sediment content that rises to at least 4.5 per cent during floods (Soil Conservation and Rivers Control Council, 1959, p. 139): this would bring the effective density well above that of sea water. It is thus possible that under some conditions the outflow of the Nuhaka River becomes hyperpycnal.

During phases of hypopycnal* outflow, the river effluent would spread out over the sea surface and would be rapidly dispersed by wave-generated currents, together with the contained sediment. During hyperpycnal flow, on the other hand, the effluent would move outwards along the sea bed, and the effect of wave action would rapidly fall off as the depth increased. Wave action would combine with the outflow in transporting the contained sediment across the shelf to the place of deposition, but the area over which the sediment was dispersed would be much less than in the case of hypopycnal outflow.

The sporadic occurrence of hyperpycnal flow

* Definitions of these terms are given in Bates (1953, p. 2125).

from the Nuhaka River would explain the following features.

(i) The uniform character of the muddy layers in B 132A and B 132B.

(ii) The dissimilarity between these layers and the typical fine-grained sediments of the bay.

(iii) The sharp base of the muddy layers. Deposition by hyperpycnal flow would be very rapid, and frequently almost instantaneous, as compared with the normal rate of deposition in the area.

(iv) The sharp top of the muddy layers. The muddy material would not be in equilibrium with normal marine sedimentation processes at the locality in question, and would suffer a certain amount of erosion after the cessation of hyperpycnal flow and before the deposition of the succeeding layer of more normal (sandy) sediment.

The isolated sharply defined band near the top of cores B 22 and B 145 cannot be explained in terms of a meteorological fluctuation, nor can it represent a volcanic eruption, as the sand fraction contains a significant proportion of non-volcanic grains. It is also unlikely to represent a phase of hyperpycnal flow from the Nuhaka River, since the band contains a higher proportion of sand than the typical muddy bands in cores B 132A-B. B 22 and B 145 are located much further from the Nuhaka River than B 132A-B, and any sediment deposited in the region of B 22 and B 145 by hyperpycnal flow from the Nuhaka should thus contain a *lower* proportion of sand than sediments deposited by the same process in the region B 132A-B. The band has evidently been formed as a result of some isolated geological event, probably occupying a very brief space of time. It is suggested that this event was a series of current surges generated by a tsunami or a train of associated tsunamis. These surges would consist of a series of oscillating currents with periods of 10-20 minutes and peak velocities ranging up to several metres per second. Owing to the great length of the tsunami waves as compared with the depth of the sea, these current velocities will extend downwards virtually to the sea bed. The effect of the sudden appearance of such currents on a sea bed consisting of sandy mud, the normal type of sediment in the area around B 22 and B 145, would be to stir the uppermost layer of sediment into suspension. This material would eventually settle out again when the tsunami currents died away, but while in suspension some of the finer fractions would be removed by turbulence resulting from tsunami current oscillations, by turbidity flow, and by any indigenous currents crossing the area. As a result, the settled-out material would form a layer somewhat coarser than the sediment from which it was derived.

The above mechanism provides an explanation for the following features:

(i) The sharp lower contact. This would represent the contact between the sediment stirred into suspension and the undisturbed sediment below.

(ii) The sharp upper contact. If the stirred-up mud were not removed from the area, the top of the band would be gradational, with the proportion of sand gradually diminishing, but removal of the mud by currents and turbulence would produce a sharp contact.

(iii) The lamination, which would be expected to result from the oscillations and variations in strength of the currents.

The tsunami surge currents must have covered a wide area, and the band must therefore have extended over many square miles at the time of its formation. The non-appearance of this band in other cores from nearby localities is presumably due to the high degree of organic disturbance in the sediment of the mud belt. Similar bands may have formed at earlier stages of sedimentation, only to be completely obscured by the activities of bottom living organisms.

Organic Structures

AGGREGATES

The smooth rounded aggregates are undoubtedly faecal pellets, and belong to the very common class of pellet having a simple ovoid shape and a smooth surface (cf. Moore, 1939, text and fig. 1 e-f). As Moore (*loc. cit.* p. 518) wrote: " . . . a large number of animals produce unsculptured pellets of the simple ovoid type, and in most deposits these are, as a result, the dominant type". No attempt, therefore, is made here to correlate the faecal pellets with any particular type of marine organism.

The rough rounded aggregates and some of the irregular aggregates are considered to be faecal pellets or particles of non-living organic matter that have undergone mechanical and chemical alteration. An excess of organic matter in a faecal pellet might cause grains in the surrounding sediment to adhere to the pellet and thus obscure the original smooth outlines. Fragments of mucus left by benthic animals, and mechanically plastic tissue derived from animals or plants, would also be capable of cementing grains in their immediate neighbourhood, and thus producing aggregates. Some of these aggregates would have an approximately ovoid shape, while others would be more irregular, although a certain proportion of the latter would tend to become rounded during mechanical analysis.

The gypsum cement present in many of the rough rounded aggregates has almost certainly formed by oxidation of local concentrations of sulphide in the sediment. The decomposition of fresh organic matter in faecal pellets or non-living organic particles would give rise to reducing micro-environments, and if Eh became sufficiently low, anaerobic bacteria would extract sulphate from the interstitial sea water and convert it to sulphide. Subsequent oxidation of the sulphide would cause a rise in the sulphate content of the interstitial water, and eventually gypsum would precipitate, this being the sulphate phase with which sea water is most nearly saturated. Within a given sulphide concentration, the newly formed gypsum would tend to grow outwards from a centre, enveloping the neighbouring particles of sediment and producing an aggregate with a spheroidal or ovoidal shape.

Oxidation was probably caused by exposure to the air after the samples were collected, as all samples were allowed to dry out before mechanical analysis. It is possible, however, that oxidation occurred within the original sediment: after the organic material at a particular centre had been dissipated, the local Eh would rise and sulphide oxidation might then take place.

Gypsiferous aggregates rather similar to those of Hawke Bay have been described by the writer from Milford Sound (Pantin, 1964). A reduction-oxidation process was invoked at this locality also, but owing to the unusual hydrological conditions in the sound it was possible to explain the process in terms of variations of Eh in the *general* environment. In Hawke Bay, however, no such general variation of Eh in the sea water can be assumed, and the formation of gypsum must therefore be explained in terms of *micro*-environments.

It will be noted that faecal pellets are here considered as sources both for the gypsiferous aggregates and for the aggregates containing glauconite. The organic component of the faecal pellets has been interpreted in both cases as the essential factor giving rise to the development of biochemical micro-environments. There is no inconsistency, however, even on the Lachlan Ridge where both minerals occur. The essential conditions for the development of glauconite include a limited supply of organic matter, whereas the reduction-oxidation cycle that produces gypsum requires an initial high content of organic matter. Gypsiferous aggregates on the Lachlan Ridge probably develop from faecal pellets with an exceptionally high organic content, while the glauconite develops in either faecal pellets with a moderate or low content of organic matter, or in formerly gypsiferous aggregates where the gypsum has dissolved away and much of the organic matter has been dissipated.

ORGANIC BURROWS

The organic burrows presumably correspond to open tubes formerly occupied by benthic animals. When one of these animals died or moved to another locality, the empty burrow would be filled in by the collapse of the walls, by the percolation of fine sediment from the walls, or by the deposition of sediment on the sea bed. Empty burrows would, of course, function as efficient sediment traps, and would be rapidly infilled by any sediment being transported across the sea bed or deposited there. The infilled burrows would thus contain, in a relatively pure form, sediment representing only a brief phase of deposition, and the material infilling a particular burrow would sometimes differ conspicuously from the surrounding sediment.

In Hawke Bay, the relatively sandy infilled burrows were presumably formed at a time when sandier sediment than the average was being deposited. Again, the relatively muddy infilled burrows were evidently formed during a phase when exceptionally muddy sediment was being deposited. The most conspicuous infilled burrows, those with a high content of volcanic ash, must have been formed about the time of a heavy eruption or series of eruptions.

MOTTLING

Mottling is the commonest type of structure in the sediments of Hawke Bay. No lamination at all is visible in the mottled sediments, and even the organic burrows are fragmentary and poorly defined. This is considered to be the result of repeated disturbance by burrowing organisms (the infauna) and by animals living on the sea bed (the epifauna). The effects of the latter group are confined to the uppermost few centimetres of sediment, but the resulting disturbance within this upper layer will be very considerable if the epifauna is abundant. The effects of the infauna extend to a depth of several decimetres, but the degree of disturbance will on the whole be less than that produced by the epifauna.

The preservation or destruction of lamination will, at any particular locality, depend on the rate of sedimentation as compared with the concentration of benthic animals and their degree of activity. These rates could be expressed as the volume of sediment deposited within a given area per unit time, and the volume of sediment disturbed by benthic animals within the same area per unit time. Completely undisturbed sediment will be laminated, but the percentage of lamination surviving will decrease as the amount of organic activity increases, and when the volume rate of disturbance reaches a value similar to the volume rate of sedimentation, lamination will remain only in small isolated pockets which fortuitously escape obliteration. When the volume rate of disturbance becomes several times greater than the volume rate of sedimentation, little or no lamination will survive, since any given portion of the sediment will almost certainly be disturbed at least once, probably several times, before organic activity at that particular level ceases as a result of burial by later sediment.

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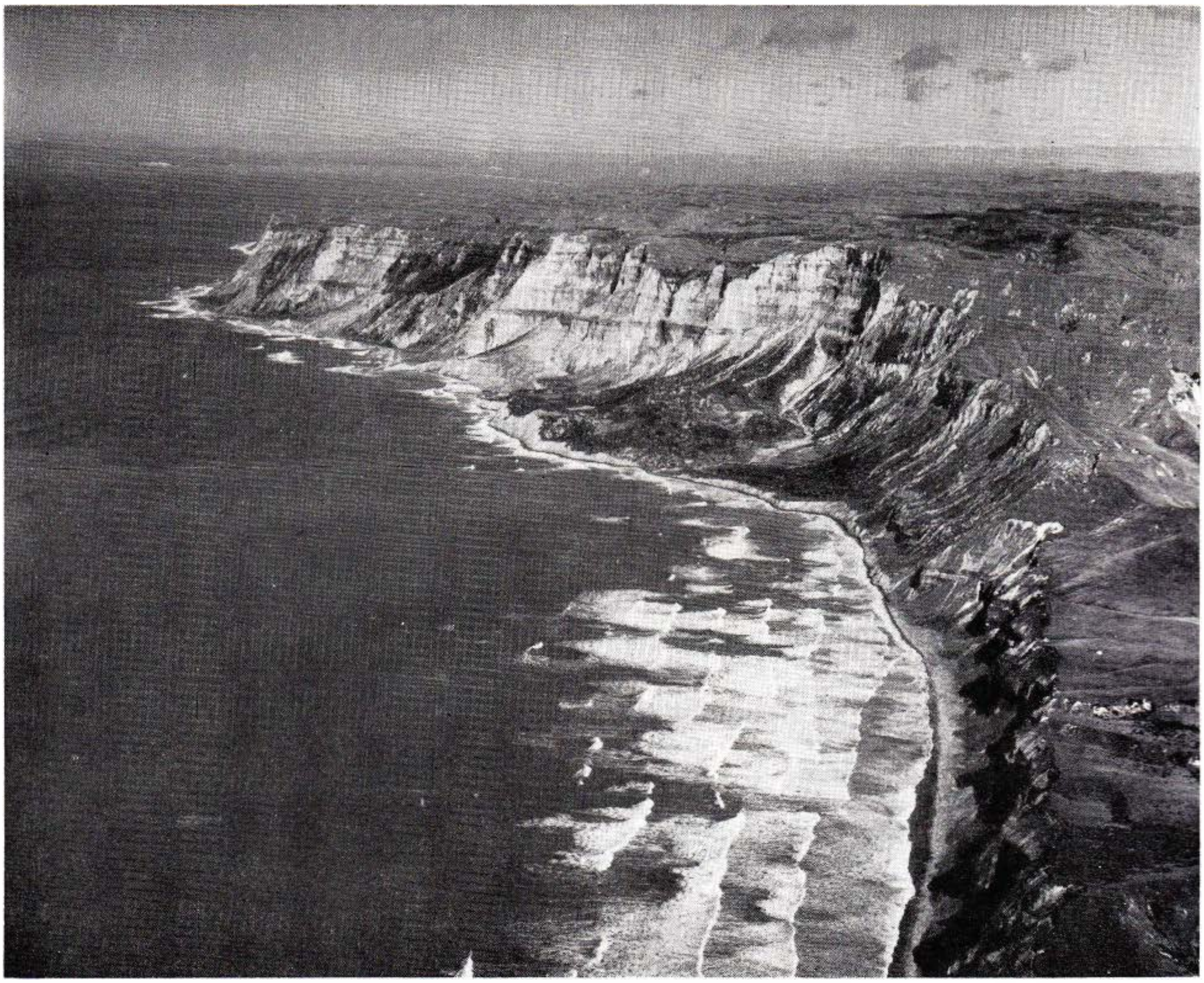
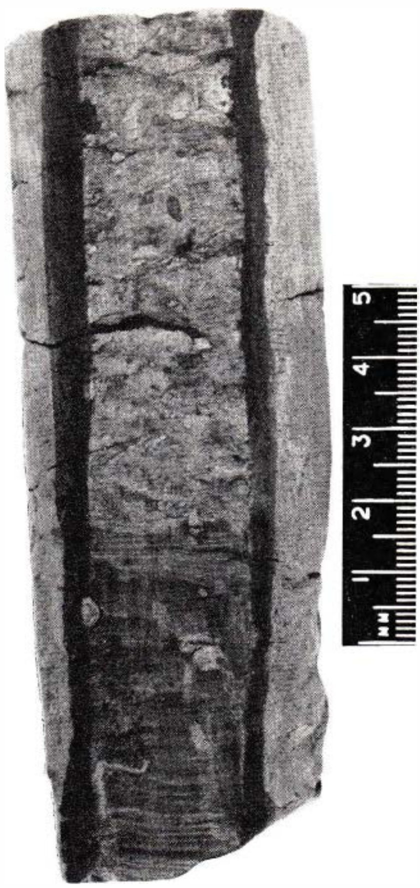
PLATES



Photograph: Whites Aviation Ltd.

PLATE 1. Nukumaruan (Lower Pleistocene) beds at Matangimomoe. The cliffs reach a maximum height of 1,293 ft. The beds in the cliff section consist of massive mudstone overlain by alternating beds of mudstone and fossiliferous sandstone, these being capped by shelly limestone. The slips in front of the cliffs took place as a result of the 1931 Hawke's Bay (Napier) earthquake.

The bluff around which the town of Napier is built can be seen in the upper left-hand corner of the photograph.



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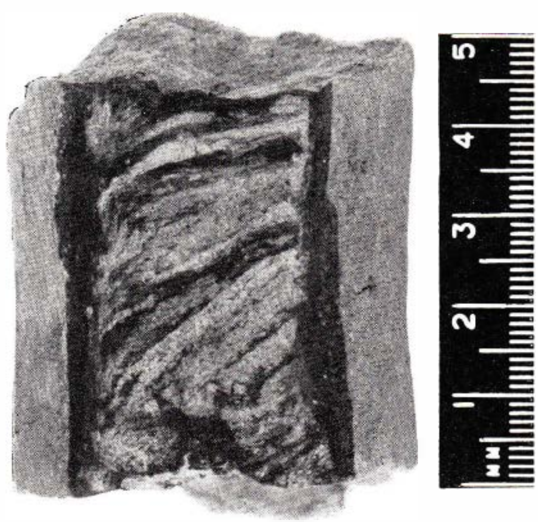

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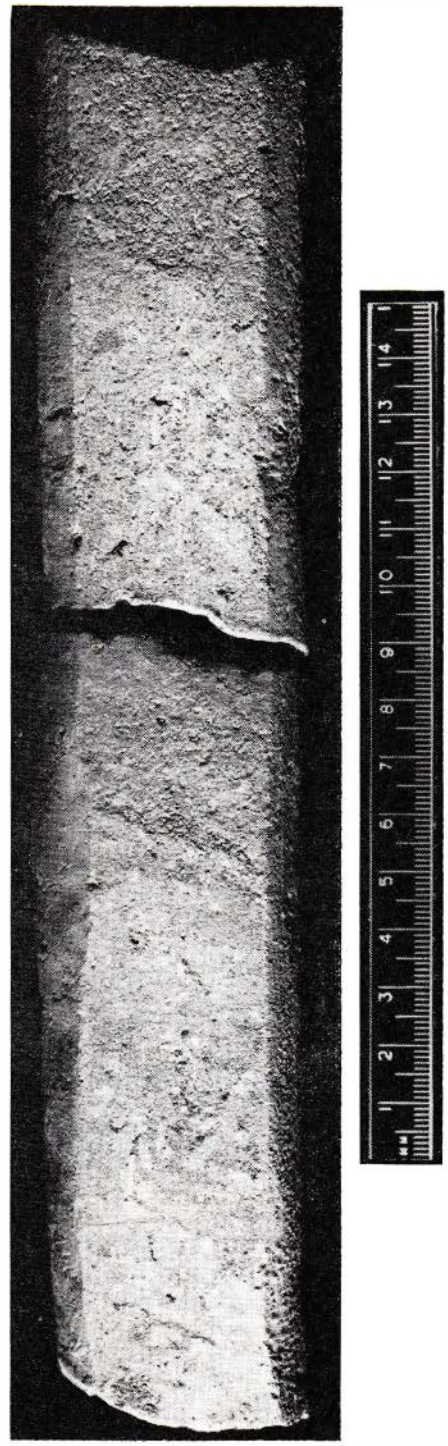

c.

Photographs: E. J. Thornley

PLATE 2. Typical structures in Hawke Bay cores (scale in cm).

a. Lamination (lower part of sample), and organic burrows, core B 124, length F1 on Fig. 8.
b. Lamination (distorted by coring), core B 124, length F2 on Fig. 8.
c. Portion of core B 133, showing diffuse banding; length F on Fig. 8.

a. b. c.

Photographs: E. J. Thornley

PLATE 3. Typical structures in Hawke Bay cores (scale in cm.)

a. Laminated layer near top of core B 145, length F on Fig. 8.
b. Organic burrows and pockets filled with white rhyolitic ash, core B 135, length F on Fig. 8.
c. Mottling, core B 123, length F on Fig. 8.

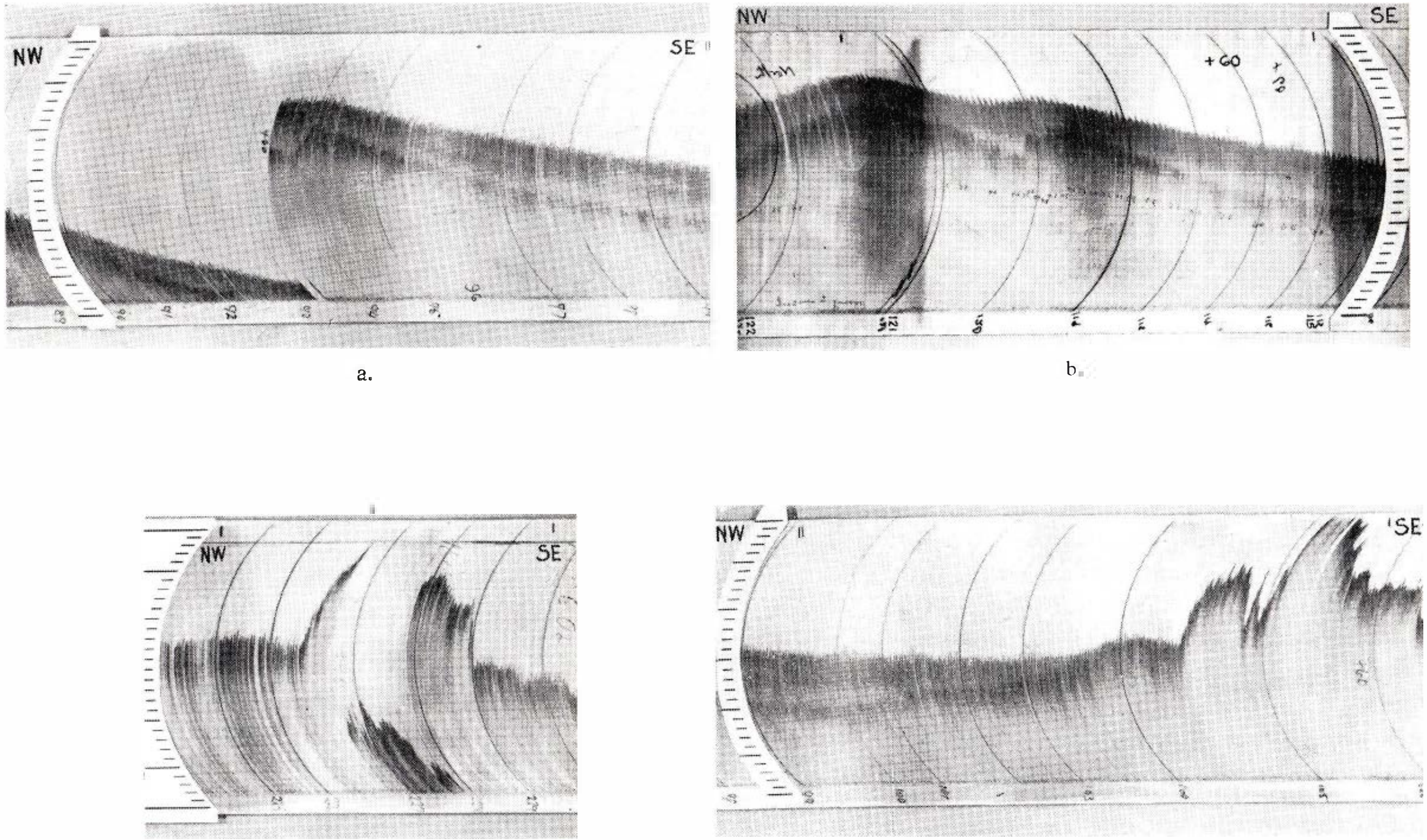

PLATE 4. Echo soundings obtained by HMNZS *Lachlan* in Hawke Bay showing:

a. Normal traverse across the Kidnappers Fault (Fixes 90 to 99, Fig. 6) and subsurface reflectors.
b. Normal traverse across the Kidnappers Fault (Fixes 121-115, Fig. 6) and subsurface reflectors.
c. A north-west to south-east crossing of Lachlan Ridge (Fixes 225-230, Fig. 6).
d. A north-west to south-east crossing of Lachlan Ridge (Fixes 99-106, Fig. 6) and subsurface reflectors.

The scale in each case is 30 fathoms across the width of the record.

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