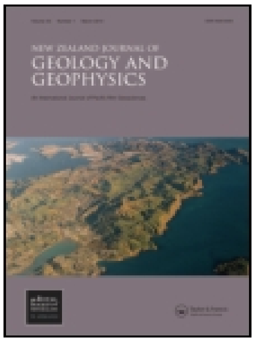


New Zealand Journal of Geology and Geophysics

ISSN: 0028-8306 (Print) 1175-8791 (Online) Journal homepage: http://www.tandfonline.com/loi/tnzg20

Recent sedimentation around northernmost New Zealand

C. P. Summerhayes

RECENT SEDIMENTATION AROUND NORTHERNMOST NEW ZEALAND

C. P. SUMMERHAYES*

New Zealand Oceanographic Institute, Department of Scientific and Industrial Research, Wellington

(Received for publication 30 July 1968)

ABSTRACT

Relict shallow water sediments, formed during the post-glacial rise in sea level, cover the continental shelf off northernmost New Zealand. Supplies of detrital sediment are negligible and biogenic skeletal debris is the only sediment component being supplied to the sea floor at present in any large quantity. Glauconite is forming over much of the region and active sediment movement is restricted to the nearshore environment.

Detrital non-carbonate sediment in the eastern part of the region has a southern basaltic provenance; that to west and north has an andesitic provenance and is derived in part from the south and in part locally.

On Maria Ridge are rich calcarenites which are forming slowly at present. On banks on the Ridge sedimentation is extremely slow and thick algal growths have accumulated around basalt pebbles left on Pleistocene marine erosion terraces.

INTRODUCTION

In this paper the textural and mineralogical characters of Recent sediments from the continental shelf and upper continental slope of northern New Zealand are studied and an attempt is made to interpret these characters as functions of provenance, transport, and deposition.

As part of a New Zealand Oceanographic Institute (N.Z.O.I.) programme of study of the character and distribution of sediment on the continental shelf of New Zealand, the writer planned and led a cruise on m.v. *Taranui* in April 1965, to the region around North Cape and the Three Kings Islands (Fig. 1). Geological samples E238–E398 collected then are supplemented by material collected by New Zealand Oceanographic Institute staff from HMNZS *Lachlan* in 1955 (samples prefixed "A") and from m.v. *Taranui* in 1962 (samples prefixed "C"). Subsequently beach samples E655–E703 were collected by the writer in December 1966. Bathymetric data from a variety of sources including the April 1965 cruise have been used to compile the bathymetry presented in Fig. 1. Samples of bedrock and other locally derived material have been used elsewhere, together with the bathymetry, in a discussion of the regional geology (Summerhayes, in press a).

*Present address: Applied Geochemistry Research Group, Geology Department, Imperial College, London S.W.7.

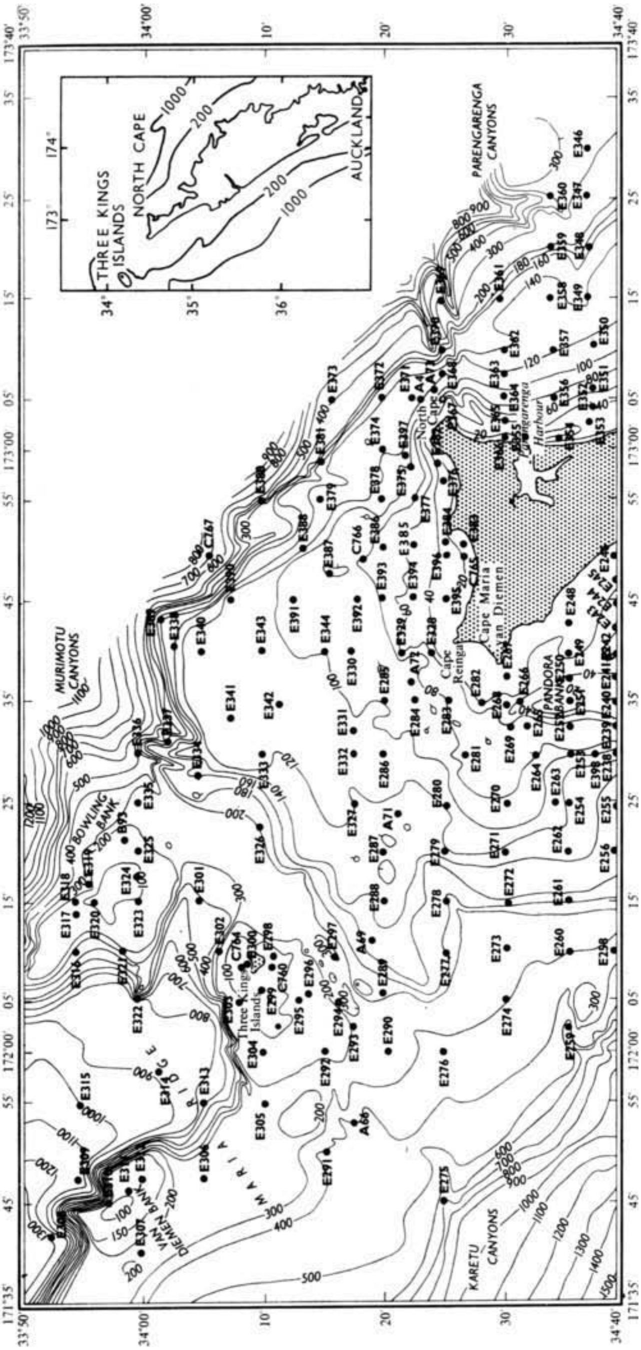


FIG. 1—Sample locations and bathymetry around northernmost New Zealand. Bathymetry based on Summerhayes (in press a).

REGIONAL SETTING

Bathymetry

Surrounding northernmost New Zealand is a continental shelf bounded approximately by the 150 m isobath (Fig. 1). This shelf is 25–30 miles wide in the north and west, diminishes to 5 miles wide off North Cape, and is only 15 miles wide east of Parengarenga Harbour. The shelf edge is indented by numerous submarine canyons, one of which extends to within 2 miles of the coast off North Cape.

North-west of Cape Reinga is a major ridge system, Maria Ridge, on which are three topographic highs with truncated tops at shelf depth; these are Bowling and Van Diemen Banks and the Three Kings shelf (Fig. 1). These shelves and banks are terraced and commonly rocky in parts which seems to indicate that they were formed by marine erosion during the Pleistocene. Preservation of Pleistocene erosion features on the shelf and the local exposure of bedrock indicates that sedimentation here has been slow or negligible since the Pleistocene. In part this certainly results from the absence of any major drainage system on the adjacent land mass.

Geology

(based on Kear and Hay, 1961; Summerhayes, in press a)

Cretaceous greywacke, sandstone, siltstone, and intermediate to basic volcanic and ultrabasic rocks are overlain by Tertiary limestone, siltstone, sandstone, and andesitic conglomerate. Outcrops of Cretaceous volcanic rocks are widespread on the sea floor west of Cape Reinga where they form a low, westward-trending ridge. This ridge presumably forms a major barrier to sediment movement as also does the constriction of the shelf off North Cape. On these grounds the shelf is divided into three regions: a western, south-west of Cape Reinga; an eastern, south-east of North Cape; and a northern, to the north of the capes.

Currents

There have been no detailed studies of currents in this region but a limited amount of drift card information is available from surveys carried out by the New Zealand Oceanographic Institute (Brodie, 1960; Garner, 1961). Major currents around northernmost New Zealand are the East Auckland Current, which moves south-east from the vicinity of North Cape, and the West Auckland Current, which moves south-east from the vicinity of Cape Reinga (Brodie, 1960, fig. 6). Drift card studies also show that currents move from west to east between Cape Reinga and North Cape before meeting the southwardly directed East Auckland Current (Garner, 1961, figs. 4, 30).

COLLECTION AND ANALYSIS

"A" samples were obtained using a Worzel sampler. An orange-peel grab was used in collecting "C" and "E" samples except where rough topography was indicated on the echo-sounder, when a pipe or cone-dredge was used for "E" samples. Dredging was carried out on all deep-water stations where there was a danger of the sample being washed out from an orange-peel grab during retrieval. To prevent samples washing out in shallow water, an inverted canvas bag was draped over the upperworks of the grab. A similar bag was normally mounted inside the cone-dredge to improve the quality of the sample obtained. Beach samples were obtained by hand.

Mechanical Analysis

After treatment with 10% hydrogen peroxide solution to remove organic matter, samples were washed in a Büchner funnel and dry-sieved to obtain fractions at 1·0 ϕ (phi) intervals (phi $= -\log_2$ diameter in mm). Where it exceeded 5% of the total, the fraction smaller than 4 ϕ (0·064 mm) was dispersed with sodium oxalate and 0·2 molar sodium carbonate and analysed by a pipette method to obtain fractions at 1·0 ϕ intervals down to 8 ϕ.

Statistical Evaluation of Data

Results of mechanical analyses were plotted on arithmetic probability paper and the curves so obtained were used to derive the median diameter (Md or 50th percentile), and sorting coefficient (σ) after Inman's method (1952).

Carbonate Analysis

Using a method described by van der Linden (1967), samples were crushed in a mortar and sieved to obtain the 1 ϕ to 3 ϕ fraction, 1 gram of which was treated with dilute hydrochloric acid. From a titration of the excess acid with sodium hydroxide solution, the carbonate percentage was determined. This method was designed to eliminate variations in carbonate content in various size fractions; its effectiveness is discussed below.

Heavy Mineral Analysis

Samples selected for heavy mineral analysis were first treated with 10% hydrogen peroxide solution to remove organic matter, then wet sieved to obtain the 1 ϕ to 4 ϕ fraction. After thorough washing to remove excess light material, 50 ml of concentrated hydrochloric acid was added to the remaining *c.* 50 gm in a fume cupboard, and on a water bath at 50°–60°C, to dissolve carbonates and iron oxides. After 20 min the sample was washed, dried, and stored in a desiccator. Heavy mineral separation was effected using bromoform (sp. gr. = 2·9) and after cleaning, washing, and drying with alcohol the heavy mineral concentrate was split into sub-fractions from which slides were made using canada balsam.

To determine the effects of granular variation on heavy mineral percentages, a normal sieve analysis was carried out on the 1 ϕ to 4 ϕ fraction used for this analysis.

Statistical Approach to Heavy Mineral Analysis

Using a petrographic microscope, mineral counts were made along adjacent grid lines until the required total had been reached. First a total of 100 grains of all types were counted to evaluate the relative proportions of opaque and non-opaque minerals. Then further non-opaque grains were counted until the total of non-opaque grains reached 100.

SEDIMENT TEXTURE

Data Evaluation

In this work only the textures of sand-silt-clay grade material (less than $-2\,\phi$ in diameter) are considered. There are a number of reasons: (1) accurately sampling and analysing the shelf gravels is difficult; (2) bimodal grain size distributions (which occur in about 60% of all samples collected) are most marked where sands and gravels are mixed; (3) Spencer (1963) found that the divisions between sands and gravels are functions not only of conditions of transport and deposition but also of grain size at origin; (4) sand and gravel particles behave differently under the same hydrodynamic conditions (Folk and Ward, 1957). This means that if textural characters are used to evaluate the effects of transport and differing hydrodynamic conditions, sands must be considered separately from gravels.

The Md (Table 1) is mainly a function of the sand population, as silt and clay occur in relatively few samples; it relates to the energy conditions of the environment of deposition. For bimodal and polymodal sediments, Md and σ only broadly indicate the average size and degree of sorting (van Andel, 1964) and must be considered as only general textural indicators.

Grain Size Distribution

In addition to plotting the distribution of Md values—values which relate closely to the *average size* of the sediment—an attempt has been made to more adequately illustrate grain size distribution by using the proportions of sand–silt–clay to define and then plot the *dominant grade or mode* (Fig. 2). For practical purposes (cf. van der Linden, 1967) clay is defined as the fraction smaller than $8\,\phi$, the lower limit of the mechanical analysis.

Only a few samples fall into the category of very sandy muds. All the others are sands, the dominant modes of which are fine (Wentworth fine and very fine; $2\,\phi$ to $4\,\phi$), medium (Wentworth medium; $1\,\phi$ to $2\,\phi$), or coarse (Wentworth coarse and very coarse; $-2\,\phi$ to $1\,\phi$). These separate types are contoured after a method used in preparation of the coastal series of New Zealand Oceanographic Institute sediment charts and described by Cullen (1966). Superimposed on sediment types are contoured Md values. From this diagram, a more realistic appraisal of sediment types and distributions can be made than from a single plot of Md values.

TABLE 1—Selected Textural and Mineralogical Characters of the Smaller Than $-2\ \phi$ Sea Floor Sediments off Northern New Zealand. Dominant modes: F = fine sand, M = medium sand, C = coarse sand, VSM = very sandy mud (*see* Fig. 2). Glauconite: * means visually determined; † signifies absent from examined sample; n.a. indicates not analysed.

N.Z.O.I. Stn No.	Md ϕ	σ	$CaCO_3$	Dominant Mode	Glauconite	Depth (metres)
E238	3·00	0·90	18·4	F	†	82
E239	1·94	0·12	8·9	M	†	38
E240	2·10	0·21	1·5	F	†	31
E241	1·90	0·20	6·8	M	†	44
E242	3·08	0·63	15·1	F	†	66
E243	1·77	0·50	15·6	M	†	57
E244	1·50	0·74	15·6	M	†	48
E245	1·99	0·25	11·5	M	†	42
E246	2·10	0·66	7·4	F	†	33
E248	1·66	0·70	11·5	M	†	37
E249	2·16	0·15	8·9	F	†	31
E250	1·84	0·40	7·4	M	†	35
E251	2·42	0·10	13·6	F	†	13
E252	1·90	0·53	30·4	M	†	60
E253	2·02	0·27	13·6	F	†	77
E254	2·49	0·47	13·0	F	*	126
E255	3·20	1·32	16·1	(VSM)	*	154
E256	2·23	1·73	31·5	M	*	157
E258	1·85	0·99	66·6	M	*	380
E259	1·96	1·44	67·1	F	*	490
E260	2·12	1·20	54·9	F	*	309
E261	1·49	1·24	60·7	M	*	161
E262	2·02	0·25	12·0	F	*	123
E263	2·05	0·37	15·6	F	*	115
E264	−0·1	1·85	76·7	C	†	71
E265	−0·3	1·15	62·4	C	†	66
E266	1·9	0·71	25·1	M	n.a.	48
E272	−1·4	0·85	94·0	C	n.a.	157
E273	1·91	1·32	38·4	M	*	252
E274	1·88	0·28	54·3	M	*	318
E275	0·95	0·71	92·4	C	†	600
E276	1·30	0·86	90·4	M	†	337
E277	2·32	0·47	47·4	F	†	177
E278	−0·45	2·07	54·4	C	n.a.	141
E279	0·14	1·20	83·1	C	†	106
E280	1·23	1·72	70·3	F	*	102
E283	−1·35	1·85	14·5	C	†	79
E284	0·5	1·58	67·5	C	n.a.	86
E285	0·84	1·88	96·5	F	†	91
E286	0·05	2·10	32·0	C	†	102
E287	1·22	1·21	76·3	C	*	121
E288	0·98	1·75	54·0	F	†	110
E291	0·08	1·19	89·5	C	n.a.	410
E292	−0·05	1·20	92·5	C	*	172
E293	0·75	1·30	86·5	M	n.a.	205
E294	1·17	1·37	93·5	M	†	245
E295	−1·35	1·72	96·5	C	†	132
E296	−1·20	1·36	97·6	C	n.a.	132
E297	−4·20	0·92	91·5	C	n.a.	315

TABLE 1—*continued*

N.Z.O.I. Stn No.	Md ϕ	σ	$CaCO_3$	Dominant Mode	Glauconite	Depth (metres)
E301	0·52	1·67	87·0	C	†	432
E302	−0·30	2·05	94·0	C	†	132
E303	−6·3	1·0	50·0	C	†	104
E305	−0·25	0·52	99·0	C	n.a.	282
E306	−1·05	1·10	100	C	n.a.	263
E307	0·51	1·10	100	C	n.a.	227
E309	1·00	1·30	89·0	C	†	1156
E310	0·20	0·95	100	C	†	99
E311	−0·35	0·88	90	C	n.a.	132
E312	−0·34	1·05	95	C	n.a.	119
E313	0·50	1·00	89·5	C	n.a.	732
E314	0·20	2·10	82	C	†	883
E317	1·10	1·00	72	M	n.a.	135
E318	0·47	0·59	96	C	†	88
E319	−0·61	1·40	98	C	n.a.	104
E321	0·50	1·37	95	C	*	166
E323	0·50	1·50	88	M	n.a.	165
E324	0·14	1·10	95	C	n.a.	168
E325	0·47	1·22	89	C	n.a.	161
E326	−3·75	0·55	99	C	n.a.	190
E327	1·81	1·52	47	F	*	119
E328	−0·90	0·70	84·5	C	n.a.	44
E329	−0·15	0·80	97·5	C	n.a.	62
E330	1·61	1·57	45·5	F	†	91
E331	−0·14	1·11	79·5	C	n.a.	102
E332	1·14	1·67	52·5	M	†	102
E333	1·60	1·32	65·5	F	*	110
E334	2·35	0·40	30·7	F	*	168
E336	1·50	1·63	76·5	F	†	157
E338	2·12	0·45	29·8	F	*	113
E340	1·98	0·55	29·0	F	*	102
E341	2·08	0·45	50·5	F	*	99
E342	1·04	2·12	54·5	F	†	106
E343	1·78	1·46	66·5	M	*	97
E344	3·10	—	35·5	F	†	102
E346	1·45	1·77	32·0	F	*	300
E347	2·30	0·94	36·3	F	*	209
E348	2·35	1·07	19·2	F	*	150
E349	3·06	1·68	59·0	(VSM)	*	121
E350	3·12	3·00	5·0	(VSM)	*	102
E351	1·78	0·57	8·3	M	*	62
E352	1·68	0·48	5·0	M	†	40
E353	2·35	0·60	6·0	F	†	27
E354	2·22	0·30	3·2	F	n.a.	17
E355B	2·23	0·32	5·0	F	†	13
E356	2·50	0·45	8·5	F	†	68
E357	3·05	1·80	73·5	(VSM)	*	113

continued . . .

TABLE 1—*continued*

N.Z.O.I. Stn No.	Md ϕ	σ	$CaCO_3$	Dominant Mode	Glauconite	Depth (metres)
E358	3·00	1·47	57·0	F	*	143
E359	2·10	1·35	37·7	F	*	172
E360	2·88	1·54	62·0	F	*	322
E361	1·97	1·77	56·5	M	*	139
E362	3·95	2·34	52·0	(VSM)	*	135
E363	4·10	2·42	46·5	(VSM)	*	110
E364	2·21	0·58	15·0	F	*	73
E365	2·53	0·20	3·0	F	†	35
E366	1·92	0·30	3·0	M	n.a.	13
E368	2·02	2·10	0	M	*	126
E369	4·52	2·74	41·0	(VSM)	*	481
E370	2·03	1·60	49·0	M	*	146
E371	2·74	2·29	66·5	(VSM)	*	121
E372	1·78	1·25	46·0	M	*	135
E373	2·30	1·54	44·5	F	*	284
E374	2·57	0·96	38·5	F	†	117
E375	3·09	1·01	44·5	F	†	88
E377	2·40	0·40	13·7	F	n.a.	75
E378	2·17	0·86	17·5	F	†	102
E379	2·15	0·34	7·1	F	*	128
E380	1·84	1·42	77·5	F	*	373
E381	2·16	1·44	70·0	F	*	150
E382	2·60	0·33	7·0	F	†	29
E383	1·95	0·53	14·5	M	n.a.	15
E384	1·50	0·73	64·0	M	†	29
E385	2·00	2·15	10·6	M	†	53
E386	1·76	1·70	13·7	F	†	66
E387	1·95	0·22	1·5	M	n.a.	88
E388	2·05	0·31	14·5	F	†	101
E389	2·14	0·29	12·5	F	†	155
E390	0·91	1·21	75·2	C	*	102
E391	1·80	1·53	24·5	F	†	95
E392	1·82	0·70	7·5	M	n.a.	84
E393	1·96	1·67	13·5	F	†	70
E394	0·50	2·20	37·5	M	n.a.	40
E395	1·80	1·95	4·0	F	†	29
E398	2·19	0·29	—	F	†	91
C764	0·66	1·22	45·0	—	†	66
C765	−0·01	1·32	7·0	—	†	21
C766	2·10	1·15	75·0	—	†	75
C767	2·46	0·37	42·5	—	†	134
A66	1·30	1·33	89·5	—	†	375
A69	0·20	—	85·5	—	†	133
A71	1·60	1·32	—	—	†	117
A72	−0·45	—	63·7	—	†	84

1. *Very Sandy Muds*

This type occurs in a discontinuous belt east and north of North Cape in 100–140 m, in similar depths a few miles west of Pandora Bank, and in one of the North Cape Canyons. Md ranges from 2·74–4·52 ϕ, averaging 3·77 ϕ.

2. *Fine Sands*

Fine sands with dominant modes between 2 ϕ and 4 ϕ occupy the greater part of the continental shelf.

1. *Eastern shelf.* Fine sands occur here in two belts on either side of the very sandy mud belt and extend to depths of 400 m.

Md values in the outer belt range from 1·45 ϕ–3·00 ϕ, averaging 2·35 ϕ; those in the inner belt range from 2·20–2·53 ϕ averaging 2·32 ϕ.

2. *Northern shelf.* A well-defined, extensive zone of fine sands occupies most of the northern shelf below 60 m and extends down to about 700 m.

Md values range from 0·84–3·10 ϕ, averaging 2·01 ϕ. The finest sands with Md values between 2 ϕ and 3 ϕ occur in the western part of the fine sand zone and along the northern continental shelf edge and upper slope.

3. *Western shelf.* Three narrow fine sand belts parallel the coast off Cape Maria van Diemen: one lies in depths of less than 20 m near the coast; a second occurs in the axis of a 40–60-m-deep depression between the mainland and Pandora Bank; a third occurs in less than 40 m on the Pandora Bank and the ridge on which the Bank is sited.

Md values in these belts range from 2·02–3·08 ϕ.

Other localised patches of fine sand occur on the shelf edge due west of Cape Reinga (Md ranges from 0·98–2·32 ϕ) and at the head of a canyon on the upper continental slope (Md ranges from 1·96–2·12 ϕ).

3. *Medium Sands*

Localised patches of medium sands are found on the eastern and northern shelves. On the western shelf parallel belts of medium sand separate the fine sand belts off Cape Maria van Diemen and tend to occur on the flanks of local ridges and depressions; a broad belt partly occupies the western shelf edge, and a small patch occurs on one of the off-shore banks.

Md values range from 0·5–2·23 ϕ.

4. *Coarse Sands*

Virtually the whole of the Maria Ridge system, including banks and troughs, is characterised by coarse sand with Md values ranging from $-2\ \phi$ to 1 ϕ. Coarse samples occur on the ridge crest and bank tops where Md vaues of $-2\ \phi$ to 0 ϕ are found.

The narrow belt of coarse sands on the rocky shelf off Cape Reinga similarly has Md values of $-2\ \phi$ to 0 ϕ.

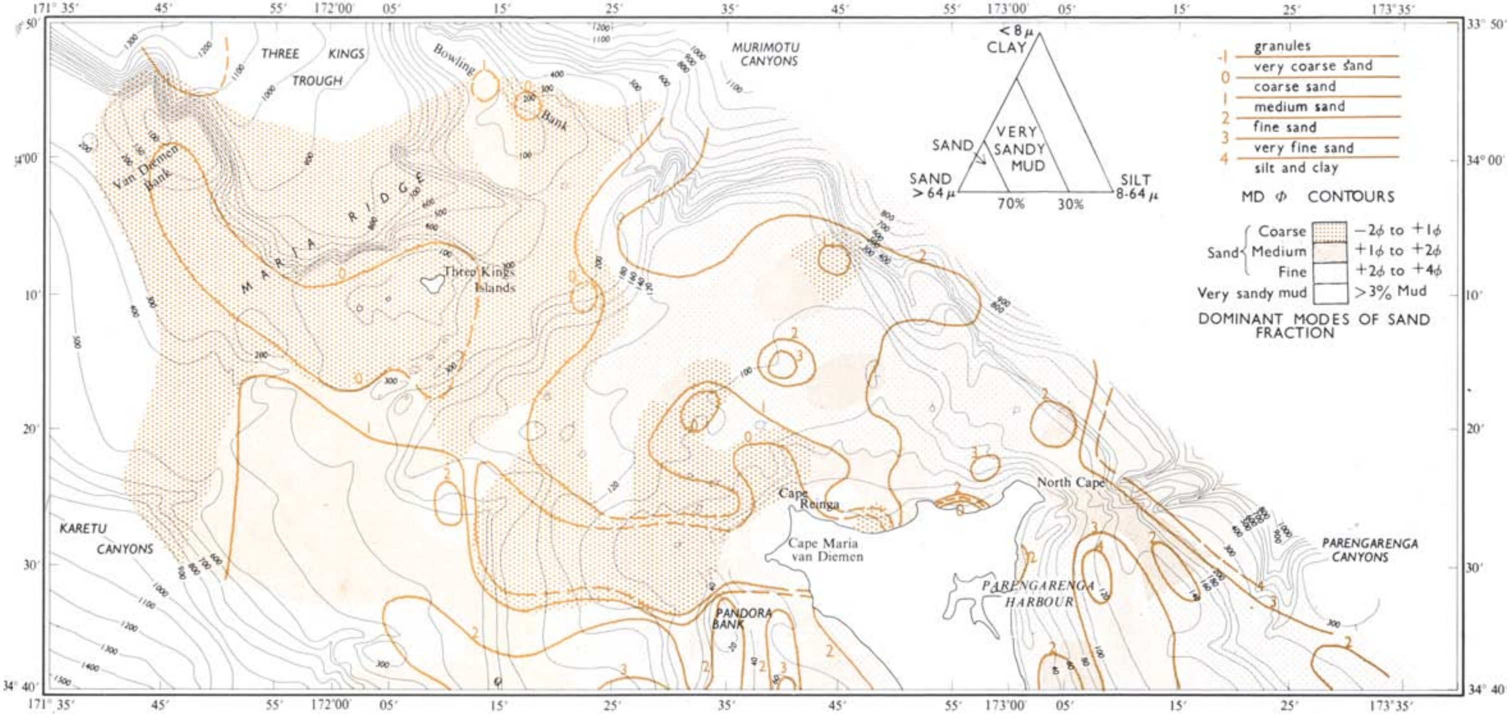


FIG. 2—Textural character of sediments: division into sand and very sandy mud is made on the basis of sand-silt-clay ratios using the triangular diagram inset (based on van der Linden, 1967, fig. 2). Sands are then subdivided according to their dominant modes after the method described by Cullen (1966). Superimposed are contoured Md ϕ values.

Boulders and Bedrock

Boulders and bedrock exposures are common on the van Diemen and Bowling Banks and Three Kings shelf on Maria Ridge, and on the continental shelf off Cape Reinga and North Cape (*see* Fig. 9 and also Summerhayes, in press a). Another phenomenon peculiar to van Diemen and Bowling Banks is the presence of large boulder- and cobble-sized, algal nodules some of which have basalt or greywacke pebble nuclei.

Beaches

Well sorted beach sands collected from the region (Fig. 3) share similar textural characteristics to sediments in shallow waters off shore (*see* Table 2). Summarising the dominant grain-size mode distributions:

(1) Ninety-Mile and Twilight Bay Beaches are composed of fine sands and there is no significant change in Md values along either beach.

(2) The beach south of Cape Reinga is more complex, grading from fine at the northern end to medium at the southern.

(3) At Spirits Bay and Tom Bowling Bay, fine sands at the western end of each beach grade to medium at the eastern ends.

(4) Between North Cape and Parengarenga Harbour are fine sand beaches.

The beaches of Tom Bowling and Spirits Bays are composite, having a relatively fine surface layer between 0·5 and 3·0 in. thick overlying coarse sands (Table 2). The fine sands are dominantly composed of detrital clastics; the coarse, of biogenic skeletal debris—chiefly broken pelycypod valves.

Dispersion

The dispersion coefficients (Table 1) used to broadly indicate the degree of sorting (after Inman, 1952) are contoured in Fig. 4 using Creager's (1964) divisions: 0·5 and less—well sorted; 0·5–1·0—moderately sorted; 1·0–2·0—poorly sorted; 2·0–4·0—very poorly sorted. Since this measure only applies to material between the 84th and 16th percentile it may, as pointed out by Folk and Ward (1957), gave misleadingly good sorting values. For the purpose of this reconnaissance, however, it is a sufficient textural indicator.

Sorting (Fig. 4) as expressed by the dispersion coefficient is best in fine sands; it deteriorates in very sandy muds and coarse sands. Particularly well sorted fine sands occur on the outer shelf over much of the area and form a separate population from similar well sorted fine sands near the coast (*see* Figs. 2 and 4).

CALCIUM CARBONATE

Calcium carbonate in the form of biogenic skeletal debris forms a considerable component of many of the sediments of this region (Table 1). Since calcium carbonate is routinely determined only on the coarser-than-3-ϕ fraction, the values given for the very sandy muds may be inaccurate: most of the sediments in this region are coarser than 3 ϕ, however.

Geographic distribution of calcium carbonate is considered in terms of the four fractions 0–25% 25–50%, 50–75%, and 75–100%. Its distribution is plotted in the form of subgrades within the dominant textural classification (Fig. 5). Those sediments containing more than 25% $CaCO_3$ are termed calcarenites after van Andel (1964). Fig. 5 is in effect a facies distribution map which will be used extensively in the interpretation of the Recent sedimentation history of the region in a later section.

75–100% $CaCO_3$

In the vicinity of Cape Reinga, the coarse sands are composed of more than 75% $CaCO_3$ with but few exceptions. Less commonly both medium and fine sands are equally rich in $CaCO_3$ particularly where they are adjacent to the coarse sands.

50–75% $CaCO_3$

The richest calcarenites of the eastern shelf occupy its deeper parts east of Parengarenga Harbour where they form very sandy muds and fine and medium sands containing 50–75% $CaCO_3$. Elsewhere the outer shelf sediments, particularly below 80 m, are similarly rich in carbonate but in shoaler depths it is rare to find such rich calcarenites.

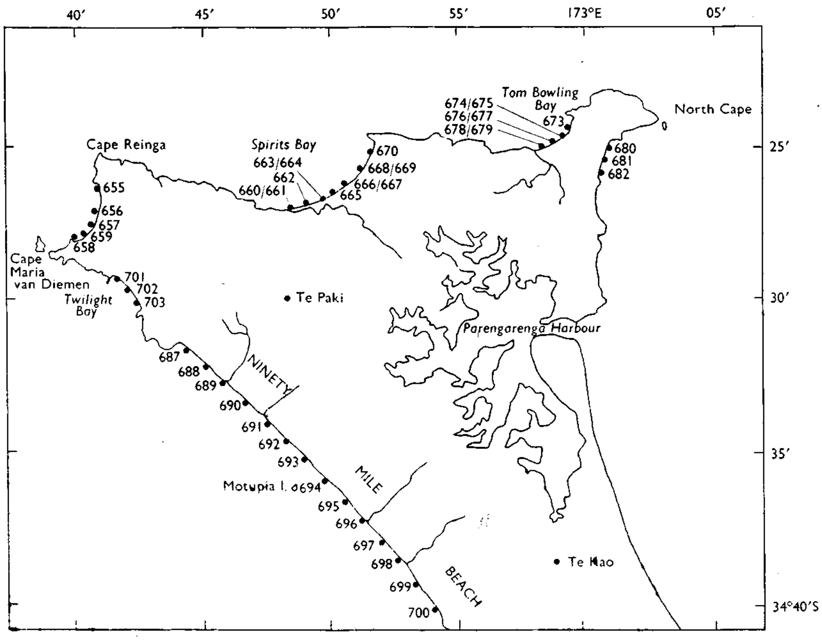


FIG. 3—Distribution of beach sand sample sites.

TABLE 2—Textural Characteristics of Beach Sands. Dominant modes: F = fine sand, M = medium sand, C = coarse sand

N.Z.O.I Stn No.	Md ϕ	σ	Dominant Mode	Surface or Buried	Locality
E655	2·24	0·25	F		Beach between Capes Reinga and Maria van Diemen
E656	1·30	0·54	M		
E657	1·10	0·70	M		
E658	1·40	0·48	M		
E659	1·50	0·57	M		
E660	0·34	0·94	C	Buried	Spirits Bay
E661	2·15	0·37	F	Surface	
E662	0·34	1·07	C	Buried	
E663	0·07	1·00	C	Buried	
E664	2·10	0·31	F	Surface	
E665	0·60	1·15	C	Buried	
E666	−0·05	1·28	C	Buried	
E667	1·88	0·50	M	Surface	
E668	1·92	0·43	M	Surface	
E669	1·08	1·17	M	Buried	
E670	2·25	0·26	F		
E673	1·05	1·17	M		Tom Bowling Bay
E674	2·10	0·38	F	Surface	
E675	−0·09	0·96	C	Buried	
E676	2·04	0·33	F	Surface	
E677	0·17	1·14	C	Buried	
E678	−1·90	—	C	Buried	
E679	2·04	0·33	F	Surface	
E680	2·33	0·25	F		South of North Cape
E681	2·18	0·47	F		
E682	2·16	0·31	F		
E687	2·56	0·21	F		Ninety Mile Beach
E688	2·50	0·19	F		
E689	2·46	0·26	F		
E690	2·49	0·23	F		
E691	2·45	0·23	F		
E692	2·53	0·22	F		
E693	2·50	0·22	F		
E694	2·56	0·20	F		
E695	2·60	0·19	F		
E696	2·51	0·23	F		
E697	2·51	0·23	F		
E698	2·60	0·20	F		
E699	2·55	0·20	F		
E700	2·54	0·23	F		
E701	2·42	0·24	F		Twilight Bay
E702	2·50	0·21	F		
E703	2·28	0·27	F		

25–50% $CaCO_3$

Calcarenites containing 25–50% $CaCO_3$ occur in zones marginal to those already discussed. Of particular interest are the discontinuous zones of this grade of calcarenite which occur near the shelf edge over most of the region. In shoaler water it occurs much less commonly in isolated patches.

0–25% $CaCO_3$

In depths shoaler than 100 m, the inshore fine and medium sand belts typically contain less than 25% $CaCO_3$ except near Capes Reinga and Maria van Diemen where there is a high carbonate anomaly. On the outer shelf such sediments occur among the discontinuous zones of calcarenites (25–50% $CaCO_3$) discussed above, east of Parengarenga Harbour and at other localised sites.

Comparison of calcium carbonate with depth (Fig. 6) shows that carbonate content tends to increase with depth.

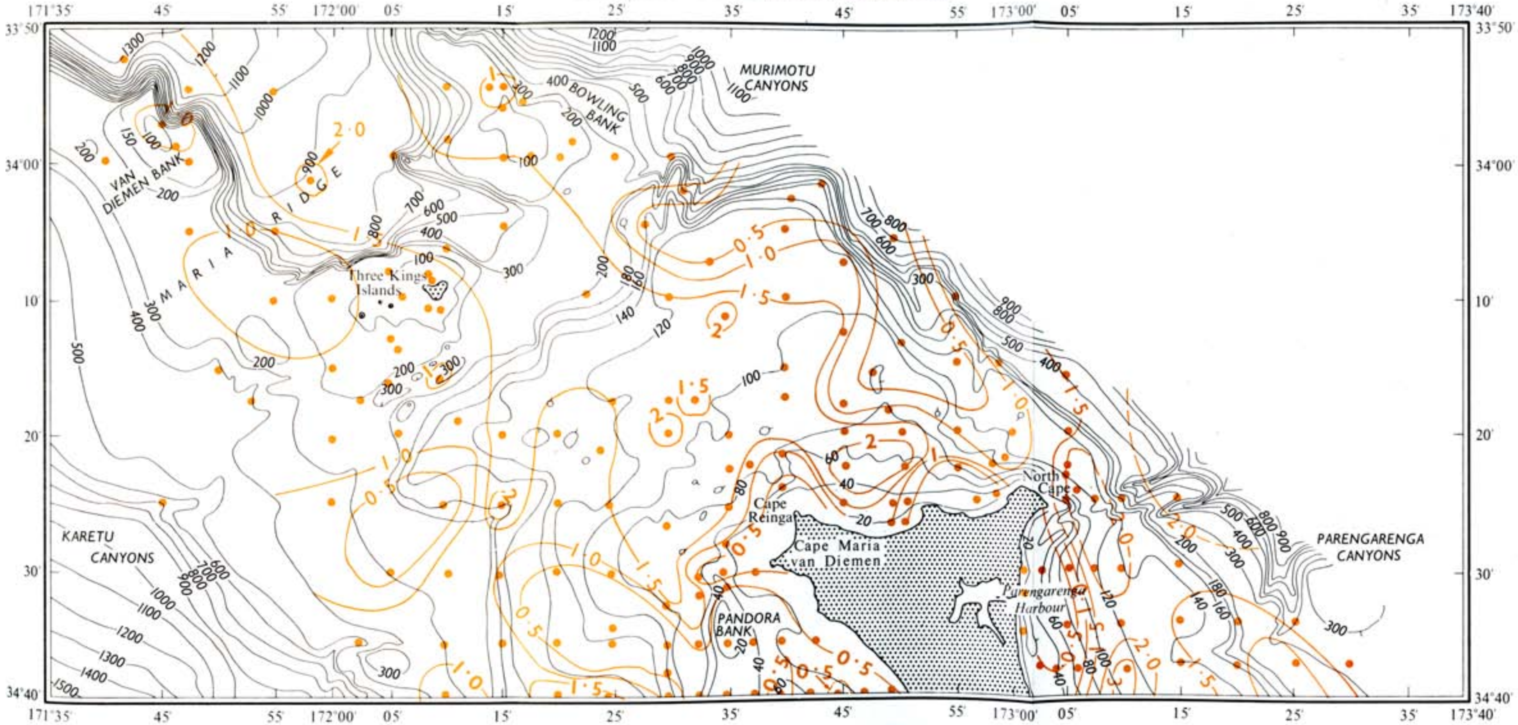
The significance of the carbonate distribution can be fully appreciated only if its distribution as one of the component minerals of the sediment is considered. Accordingly a coarse fraction analysis (*after* Shepard and Moore, 1954) was undertaken to determine the form and distribution of carbonate within selected sediment samples.

COARSE FRACTION ANALYSIS

Grain counts on each sieve fraction coarser than 4 ϕ gave data on the distribution of different mineral components within the sediments (Fig. 7). Major components of the sediments here are biogenic and detrital with a subordinate contribution from the authigenic mineral glauconite. Biogenic material chiefly consists of molluscan skeletal debris and bryozoan fragments with minor amounts of sponge spicules, echinoid and serpulid-tube fragments, foraminifera, and faecal pellets. Detrital clastic grains were not separated into mineral species but the rather general observation was made that sediments of the eastern shelf were dominantly quartzose whereas on the western shelf quartz and feldspar tend to be in approximately equal proportion. Good examples of the detrital mineralogy of off-shore sediments are exhibited by the white quartz sands from around Parengarenga Harbour (where sand is dredged for use in glass manufacture) and the brownish-pink sands of Ninety Mile Beach. Heavy minerals do not appear to form more than 10% of the detrital mineral assemblage off shore.

It is clear from Fig. 7 that in fractions coarser than 1 ϕ, molluscan skeletal debris with subordinate bryozoan remains form the major sediment components. In finer grades detrital minerals predominate and pumice fragments, glauconite, and foraminifera form the most common subordinate components.

Differences in the supply of the two major sediment components, biogenic and detrital, will obviously considerably influence the textural character of the sediment. For example, where carbonate sedimentation is high, Md is



N.Z. Jl Geol. Geophys. 12(1), 1969

FIG. 4 Contoured sorting or dispersion values (σ). <0.5 = well sorted; 0.5 – 1.0 = moderately sorted; 1.0 – 2.0 = poorly sorted; 2.0 – 4.0 = very poorly sorted (after Creager, 1964).

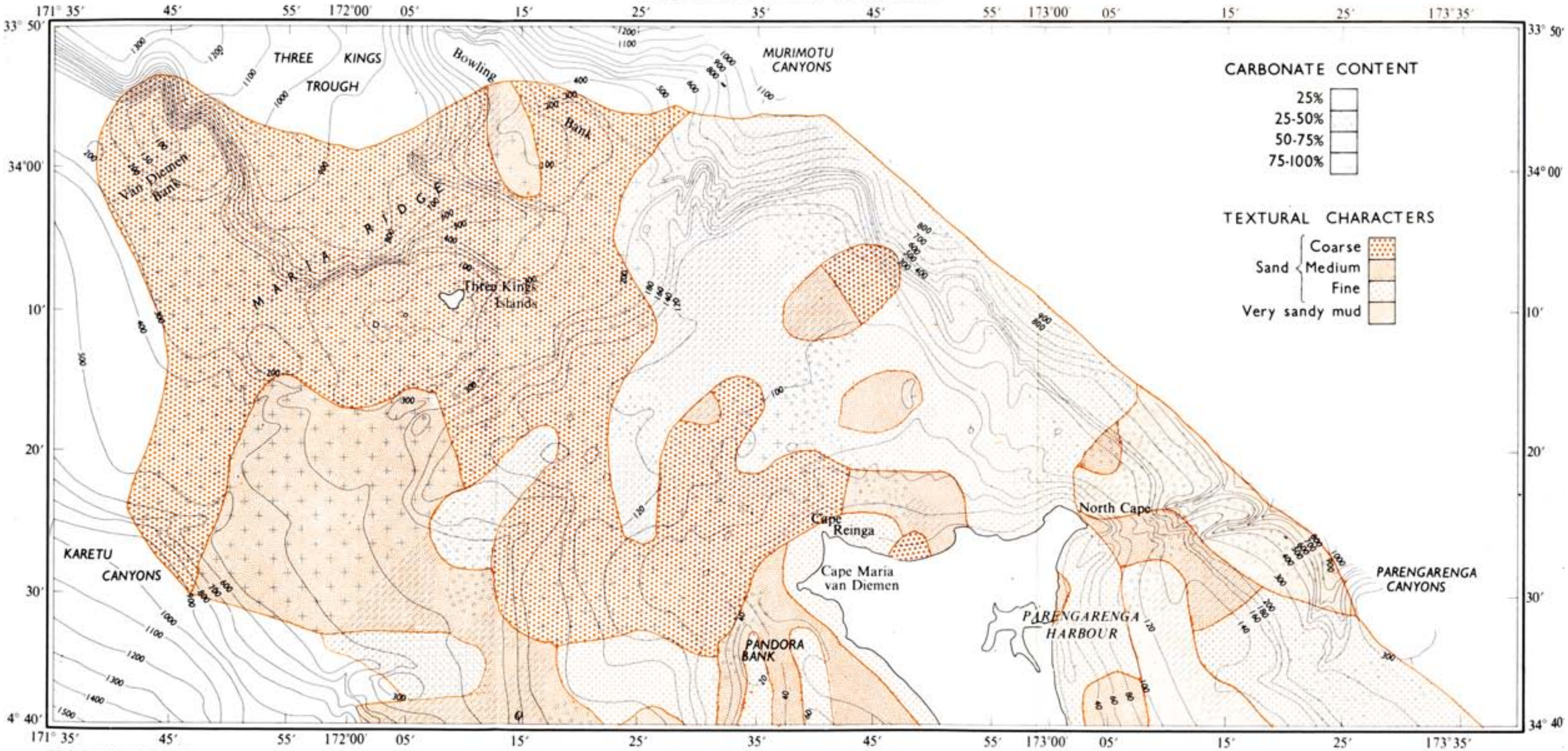


Fig. 5—Facies distribution. $CaCO_3$ values are superimposed on the grain-size distribution outlined in Fig. 2. Those sediments containing >25% $CaCO_3$ are calcarenites except when they have the texture of very sandy muds, in which case they are regarded as slightly muddy calcarenites; those containing <25% $CaCO_3$ are sands or very sandy muds.

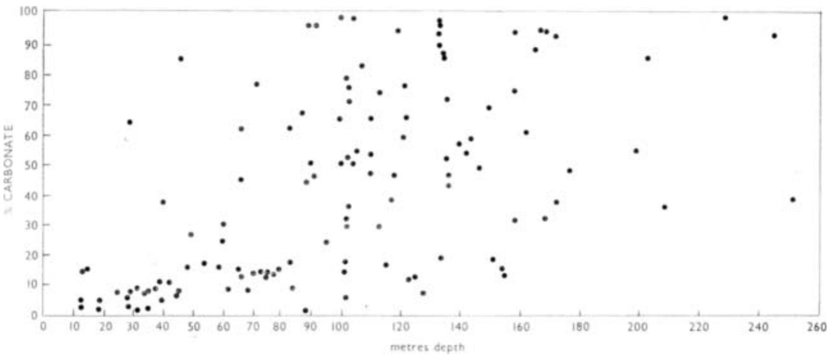


FIG. 6—Variation of $CaCO_3$ percentage in relation to depth in sediments from less than 260 m. Samples plotted are from Table 1.

biased towards coarser grain sizes; the converse applies where detrital sedimentation predominates (Fig. 8). Similarly, sorting in the fine non-calcareous sands is much better than in the calcarenites (cf. Figs. 4 and 5). This is because smaller but heavier detrital grains behave in the same way as relatively larger but lighter carbonate grains under the same hydrodynamic conditions.

GLAUCONITE

A binocular microscope was used to determine the presence of glauconite, an authigenic mineral observed in 46 out of the 111 analysed samples (Table 1). Glauconite is widespread on the continental shelf (Fig. 9) where it occurs only in depths greater than 40 m on the eastern shelf and in deeper than 100 m over the rest of the region. It is also found in sediments from van Diemen and Bowling Banks on the Maria Ridge.

This mineral chiefly occurs here as the internal casts of Recent foraminiferal tests, a form common in New Zealand shelf sediments (Pantin, 1966; Seed, 1968; Summerhayes, in press, b). Occasionally it occurs as rounded botryoidal grains displaying syneresis cracks; these may be replaced faecal pellets. Some of the foraminiferal casts consist of a pale yellow, red-brown mineral which may be limonite (Pantin, 1966) although this too could be glauconite (*see* Seed, 1968).

Where it forms foraminiferal casts glauconite is dominantly to be found in the less-than-2-ϕ fraction (*see* Fig. 7); where present as dark green pellets, it occurs in the coarser fractions where it may form up to 40% of individual size fractions as at Sta. C755 (Fig. 7).

HEAVY MINERALS

Hornblende, hypersthene, and epidote are the most abundant translucent heavy minerals (Table 3). Minor amounts of augite and enstatite, spinel, and garnet are also recorded. The hornblende is dominantly green and pleochroic although red-brown basaltic hornblendes are recognised as are, more rarely, blue varieties.

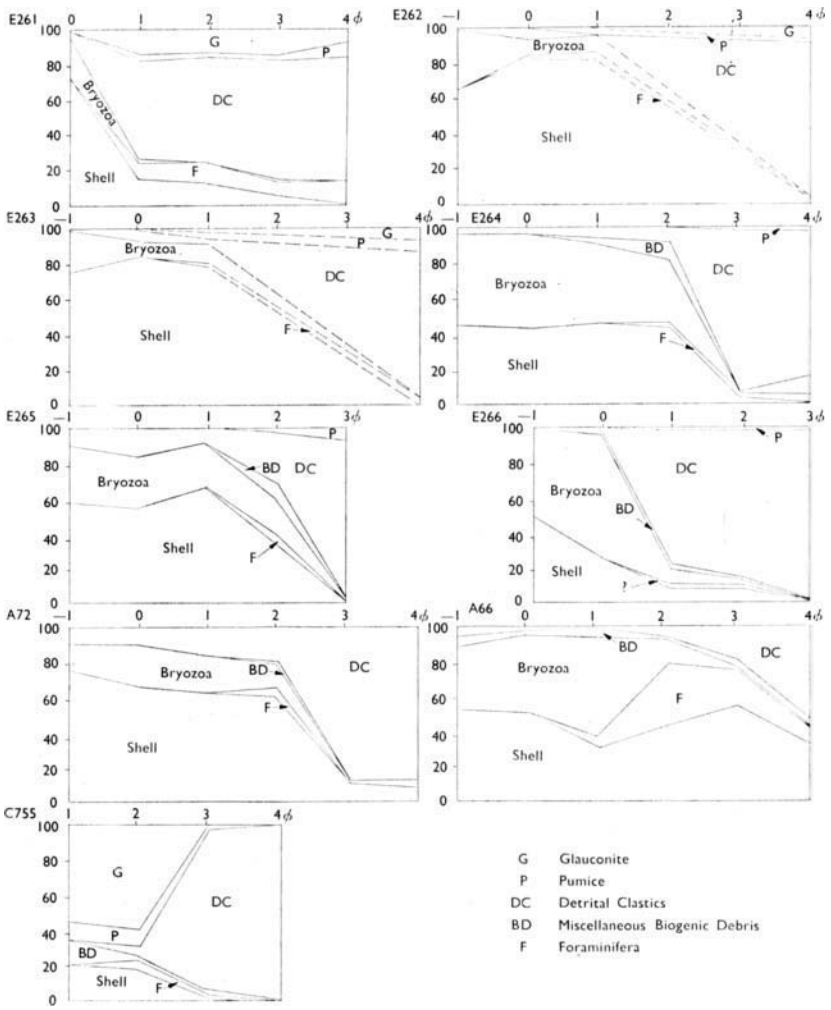


FIG. 7—Coarse fractions analyses of selected sediment samples. These are achieved by plotting the percentages of grains of different components in each size fraction of the sediment above 4 ϕ. Samples 261–6 represent a profile from deep to shallow water. It is obvious that towards shallow water, the percentage of foraminifera decreases and that of bryozoan fragments increases relative to molluscan skeletal debris (shell). Sample C755 is sited just outside the study area some 2 miles due south of sample E240. Miscellaneous biogenic debris includes sponge spicules, echinoid plates, serpulid-tube fragments, and faecal pellets.

A simple multivariate analysis of the heavy mineral data is attempted here, to classify the samples into natural groups. Data are plotted on four triangular diagrams taken to represent the four faces of a tetrahedron (after Pettijohn, 1957), the apexes of which are represented by opaques, hornblende, pyroxene, and epidote (Fig. 10). It is readily apparent that the data fall into two natural groups, one containing all sediments from the eastern region, the other containing most sediments from the western or northern regions. Since the differences are distinctly geographical these groups can be regarded as distinct mineral provinces (Fig. 11). The eastern province is relatively enriched in pyroxenes and opaques, the western in hornblende and epidote. Boundaries between the two groups in each of the four triangular diagrams (Fig. 10) are selected as follows: the pyroxene, hornblende, and opaque boundaries are selected such that the lowest pyroxene and opaque values and the highest hornblende values from the eastern region are included in one mineralogical group; the epidote boundary is selected on the same grounds but extended slightly to include sample E380 because (a) it is geographically part of the eastern region and (b) its pyroxene, opaque, and hornblende contents are typical of the eastern region. The close interrelation between the four variables in each group indicates that the selected boundaries are both mineralogically and geographically significant and it is justifiable to regard these groups as distinct mineralogical provinces.

All samples from the eastern province (Fig. 11) share the same basic proportions of hornblende, epidote, opaques, and pyroxene. This province covers the eastern shelf and associated beaches, Tom Bowling Bay and

Text continued on p. 192

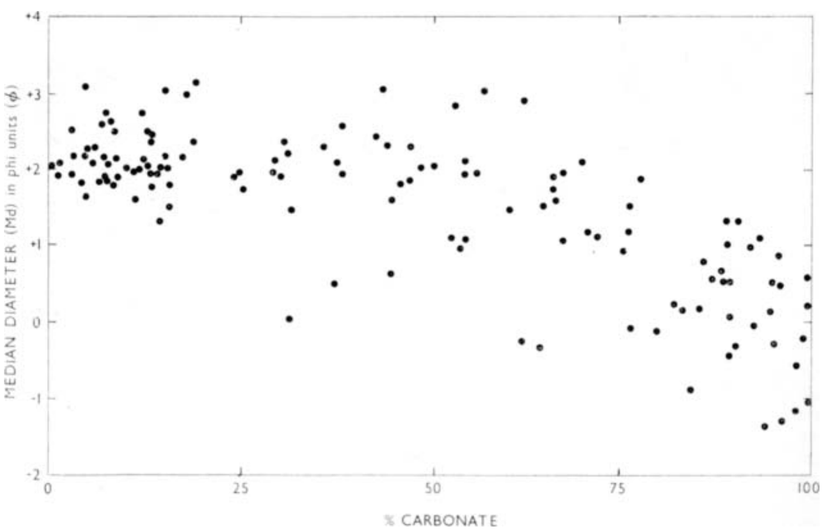


FIG. 8—Variation of $CaCO_3$ percentage with respect to median diameter expressed in phi units. Samples plotted are from Table 1 and exclude those with median diameters less than $-2\ \phi$.

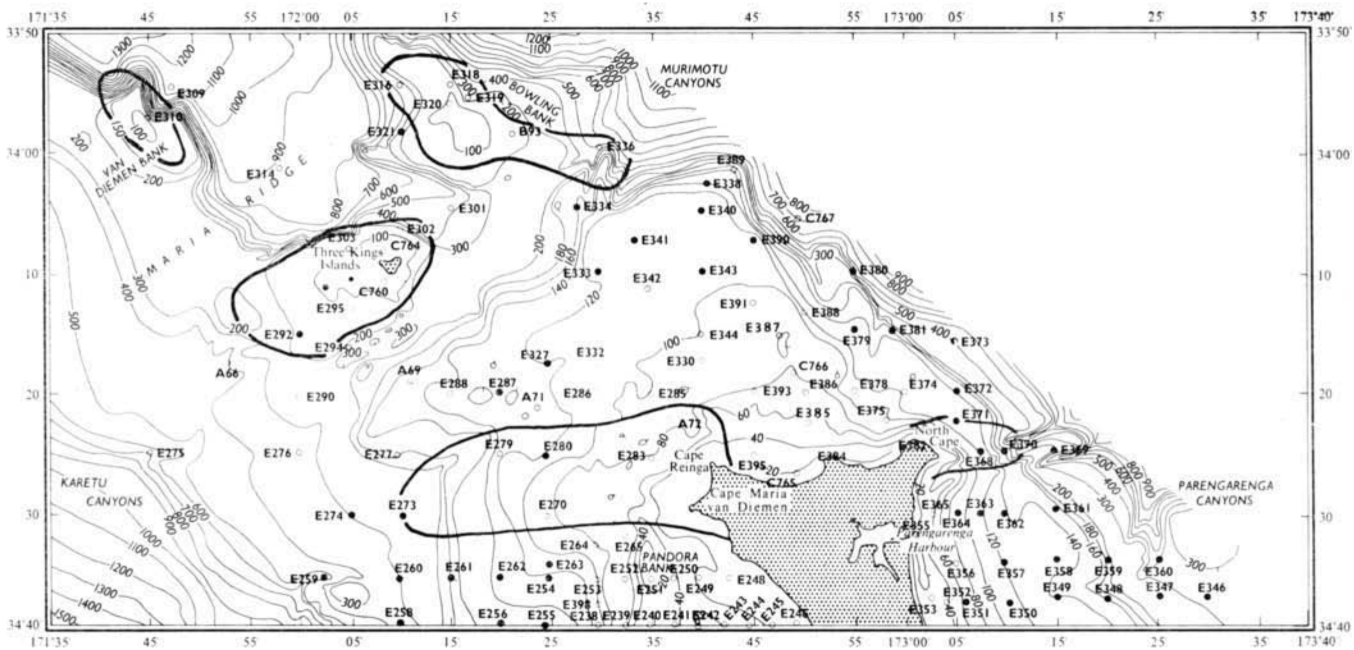


FIG. 9—Location of glauconitic and non-glauconitic samples. Glauconitic samples are shown by solid dots and non-glauconitic samples by open circles. Boulders of bedrock (described by Summerhayes, in press a) occur within the areas encompassed by heavy lines.

TABLE 3—Heavy Mineral Grain Count Data and Md of Non-Carbonate Fraction Used for Analysis. * = Biotite. All samples are "E" samples (*see* p. 172)

E. Stn. No.	Altered	Opaque	Trans-lucent	Epi-dote	Green Horn-blende	Brown Horn-blende	Hypers-thene	Ensta-tite	Augite	Spinel	Un-identi-fiable	Md
238	8	3	89	26	40	25	8	—	1	—	—	2·48
241	15	10	75	27	25	25	13	4	4	2	—	2·77
244	14	4	82	31	28	24	11	1	2	3	—	2·74
248	21	4	75	32	19	28	9	9	2	1	—	2·88
250	12	4	84	22	24	30	14	4	1	5	—	2·60
252	14	7	79	38	26	27	4	—	1	4	—	2·81
254	15	12	73	35	24	26	9	1	2	3	—	2·83
256	19	6	75	48	21	18	11	—	2	—	—	2·23
258	3	8	89	12	12	—	7	1	—	2	66*	2·97
262	14	6	80	33	32	15	11	5	1	3	—	2·69
265	32	18	50	70	10	4	—	—	16	—	—	2·90
274	22	13	65	74	6	6	14	—	—	—	—	2·61
277	22	13	65	56	18	9	13	2	2	—	—	2·75
279	14	10	76	46	26	10	11	5	2	—	—	—
280	30	13	57	42	30	16	11	1	—	—	—	2·57
283	20	9	71	50	8	7	30	5	—	—	—	2·35
285	12	7	81	40	18	27	10	3	—	2	—	2·60
286	13	5	82	50	9	11	30	—	—	—	—	2·40
287	26	7	67	50	26	10	6	4	4	—	—	—
332	22	5	73	50	12	23	13	2	—	—	—	2·55
333	15	10	75	37	22	20	13	1	—	7	—	2·68
334	14	11	75	44	18	22	9	3	3	1	—	2·52
340	12	6	82	40	16	31	12	—	—	1	—	2·63
342	18	20	62	41	19	20	13	—	1	6	—	2·59
343	20	6	74	60	8	9	16	5	2	—	—	2·35
344	23	13	64	46	26	20	5	2	1	—	—	2·57
346	12	12	76	29	15	3	38	8	7	—	—	3·22
347	15	11	74	45	21	6	18	5	3	—	2	2·45
348	12	13	75	39	20	6	31	3	—	—	1	2·77
349	13	8	79	33	28	3	22	7	—	—	7	3·03
351	15	7	78	41	15	1	37	4	2	—	—	3·11
353	18	60	22	52	15	7	19	7	—	—	—	2·40
355A	25	28	47	35	35	7	22	—	1	—	—	2·40
355B	36	22	42	37	33	5	22	—	3	—	—	2·26
356	27	17	56	53	17	3	24	—	3	—	—	2·44
358	11	5	84	17	28	5	30	5	5	—	10	3·04
359	13	14	73	34	27	5	25	6	3	—	—	2·71
362	12	6	82	38	18	8	31	3	2	—	—	3·16
364	24	12	64	47	24	7	18	1	2	—	1	2·71
368	20	18	62	58	12	1	27	1	—	—	1	2·42
370	11	8	81	29	25	11	25	8	2	—	—	2·96
372	12	24	64	32	19	3	37	5	1	—	3	2·57
373	9	12	79	38	17	10	27	5	1	—	2	3·27
375	21	4	75	32	23	14	27	2	—	2	—	3·22
378	15	1	84	43	20	18	14	3	—	2	—	3·00
379	13	4	83	33	28	20	18	—	—	1	—	2·70
380	29	13	58	53	5	21	19	—	2	—	—	2·43
382	22	16	62	57	3	1	35	4	—	—	—	2·70
384	16	6	78	66	—	2	25	6	—	—	1	2·17
385	14	3	83	41	20	16	19	—	1	3	—	2·62
386	13	10	77	44	17	21	15	1	2	—	—	2·42
388	19	2	79	30	22	33	12	1	—	2	—	2·61
389	19	7	74	41	24	28	4	—	—	3	—	2·71

continued . . .

TABLE 3—*continued*

E. Stn. No.	Altered	Opaque	Trans-lucent	Epi-dote	Green Horn-blende	Brown Horn-blende	Hypers-thene	Ensta-tite	Augite	Spinel	Un-identi-fiable	Md
391	13	4	83	35	20	32	11	—	—	1	1	2·61
393	16	20	64	52	13	18	17	—	—	—	—	2·46
395	9	3	88	43	16	26	14	—	1	—	—	2·56
656	31	10	59	54	9	8	16	11	2	—	—	1·83
661	21	1	78	44	5	1	42	6	2	—	—	—
670	27	3	70	39	7	2	39	9	4	—	—	2·28
673	30	5	65	47	18	3	22	6	4	—	—	2·10
679	28	1	71	48	10	—	35	5	2	—	—	—
681	50	4	46	38	27	7	21	5	2	—	—	2·34
687	15	1	84	15	41	41	1	—	1	1	—	2·53
692	20	3	77	20	34	40	6	—	—	—	—	2·53
699	16	3	81	25	36	32	3	2	1	1	—	2·53
702	15	14	71	19	37	37	6	—	1	—	—	2·50

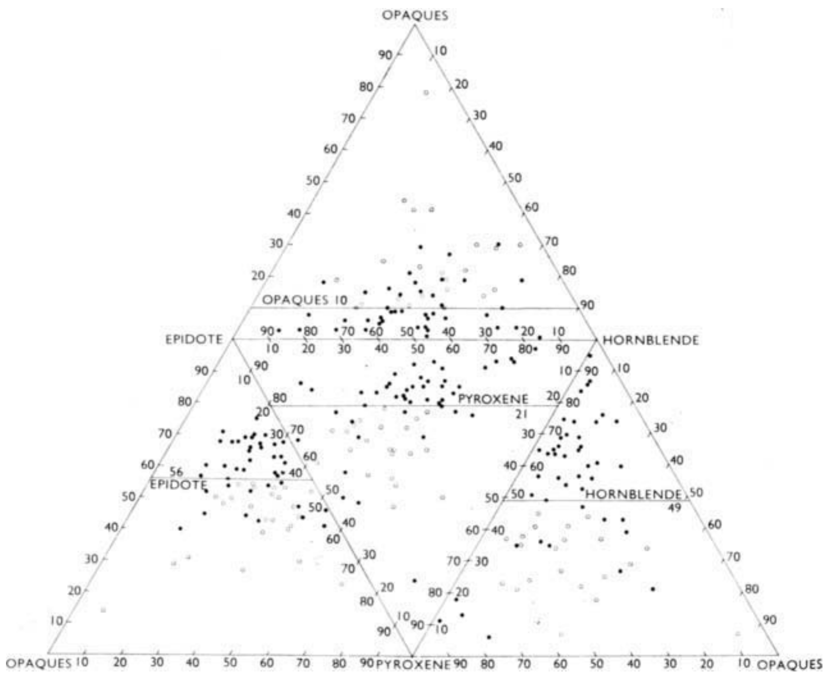


FIG. 10—Mineralogical characteristics of eastern and western heavy mineral provinces. Eastern province samples are open circles; western province samples are solid dots. The triangular diagrams represent the four faces of a tetrahedron (*modelled on* Pettijohn, 1957). The additional horizontal lines mark the boundaries of the eastern and western provinces (*see* text for further discussion).

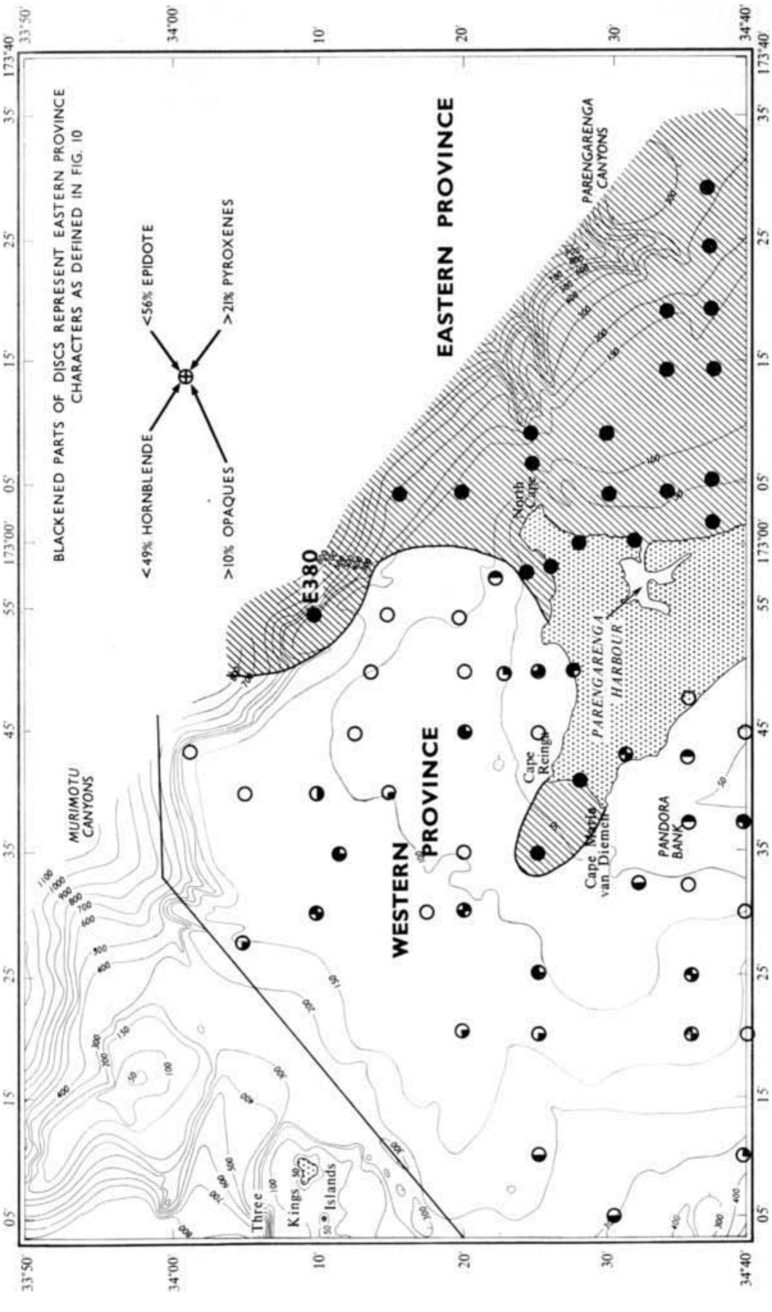


FIG. 11—Geographical extent of heavy mineral provinces.

the outer shelf sediments north of North Cape as well as a small patch of sediment on the beaches near Cape Reinga and the off-shore sediments near that cape.

Sediments of the western region are non-uniform in the sense that they may share in part some of the characteristics of the eastern province. They are distinguished as a separate province by never sharing all the characteristics of the eastern province. Were a more quantitative approach adopted, more refined sample groupings might be possible for the western province. However, for the present purposes this simple division into two provinces is adequate and meaningful. The resistances to erosion of hornblende, pyroxene, and epidote are different. Consequently over a period of time these minerals may tend to become concentrated in different size fractions of any sediment body subject to erosive processes such as wave action or transport. To determine whether observed mineral variations were a function of grain size, the 1 ϕ to 4 ϕ non-carbonate fractions used for heavy mineral analysis were sieved and their average grain sizes (Md) were compared with their heavy mineral contents (Fig. 12). Dependence on grain size was established for epidote and the opaques, which tended to decrease with decreasing Md, and, less readily, for pyroxene, which showed a tendency to increase in the finer sediments. Variation in hornblende appeared to be more or less random with respect to Md. It must be deduced that regional grain size variations influence regional mineral variations. However, it is also found that the spread of Md values of these detrital fractions is the same in each of the mineral provinces defined below (Fig. 12). Thus, although grain size variations within each province may cause mineral variations, mineralogical differences between the two provinces cannot be a function of grain size. Instead the variation is most probably caused by the fact that each province has a difference source.

Quantitative distribution maps (Fig. 13A–D) obtained from grain counts on heavy minerals may provide information of the source and dispersal patterns of these minerals. By drawing lines along the axes of major and minor concentrations, vectors representing transport directions may be obtained (*see* Moore, 1968). Distribution vectors for the minerals considered show a striking pattern similarity which indicates that mineral distribution is probably controlled by the prevailing current system. In simple terms it is apparent that the major distributional vectors on the eastern and western shelves broadly parallel the coastline whereas on the northern shelf they are oriented north-west - south-east across the shelf.

Hornblende varies more or less randomly with grain size so directions of decreasing concentration along distributional vectors probably do represent directions of transport (*compare* Moore, 1968); such directions are marked where possible (Fig. 13). Because the opaques, epidote, and pyroxene are known to have some dependence on grain size, the directions of decreasing concentration along their distributional vectors do not necessarily solely reflect transport directions.

Coastal Profiles

The shape of coastal profiles (Fig. 3) and the textural characters of beach sands in bays allow prevailing directions of longshore current movement to be assessed. Profiles of Tom Bowling and Spirits Bays indicate that currents are moving west along the coast, an observation supported by the observed increase in sediment fineness in a westerly direction.

On Ninety Mile Beach, coastal profiles suggest a northward longshore drift component (*see* Cotton, 1951) which probably continues north to Cape Reinga since on the beach south of the cape sediments increase in fineness toward the north.

On the eastern shelf the coastal profiles are less easily interpreted which suggests that longshore drift may be negligible. However, the prolongation of the North Cape canyon to within 2 miles of the shore south of the cape (Fig. 1) suggests that northerly currents may be active here in shallow water. The reason for assuming this is that the canyons were probably cut by the movement of sediment-laden water, and the shape of the canyon suggests it was cut by a "stream" deflected eastward as it approached the cape from the south. That this is a zone of active sediment movement is indicated by the absence of glauconite in depths of less than 40 m (Fig. 9).

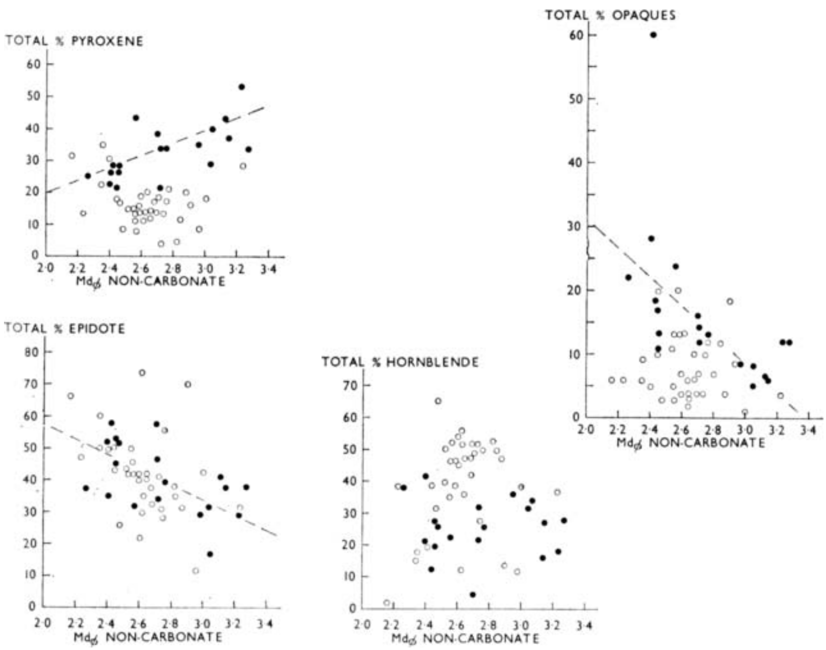


Fig 12—Relation of heavy minerals to Md ϕ non-carbonate fraction. Open circles denote western province samples and black dots, eastern province ones. Approximately linear relations to grain size apparent for opaques, epidote, and pyroxene among the eastern province assemblage are represented by dashed lines. These trends are less apparent for western province assemblages.

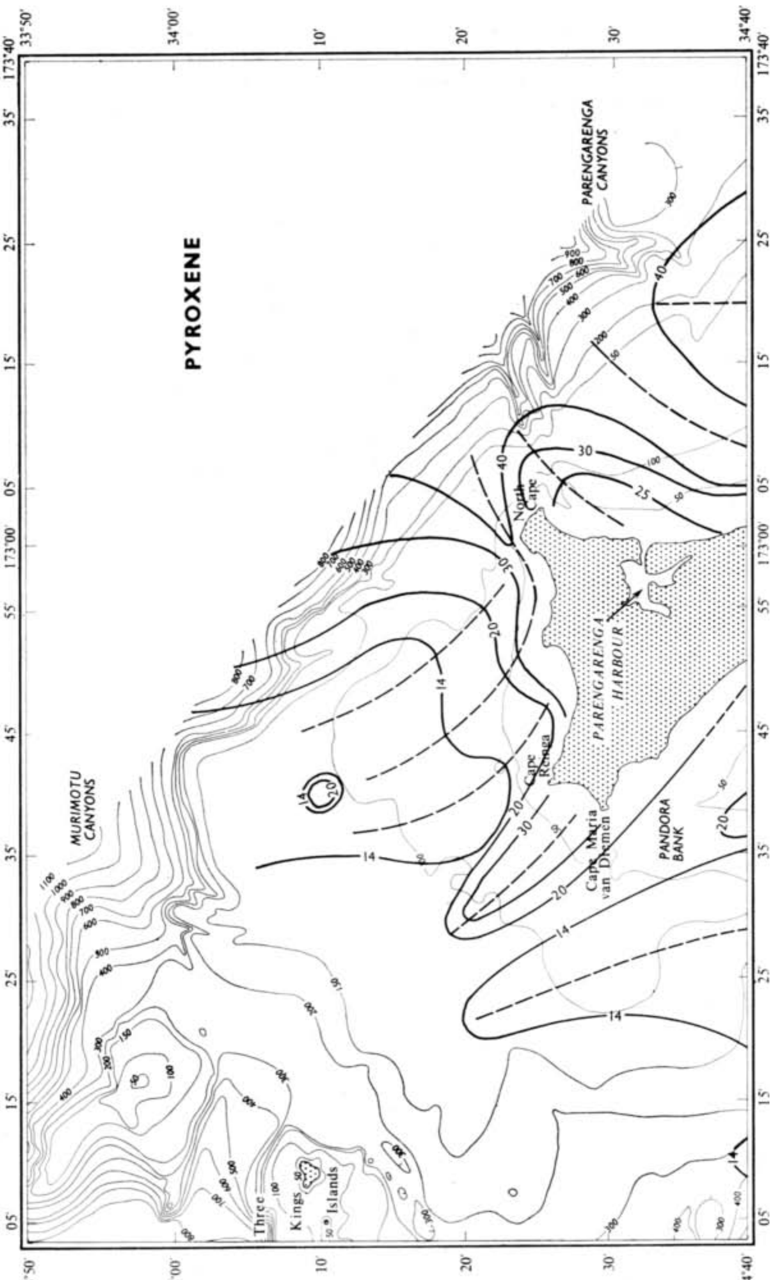


FIG. 13 A–D—Geographical distribution of heavy minerals; A = Pyroxene. Total values are contoured and distributional vectors (broken lines) are erected along axes of contour salients (*see* text for discussion).

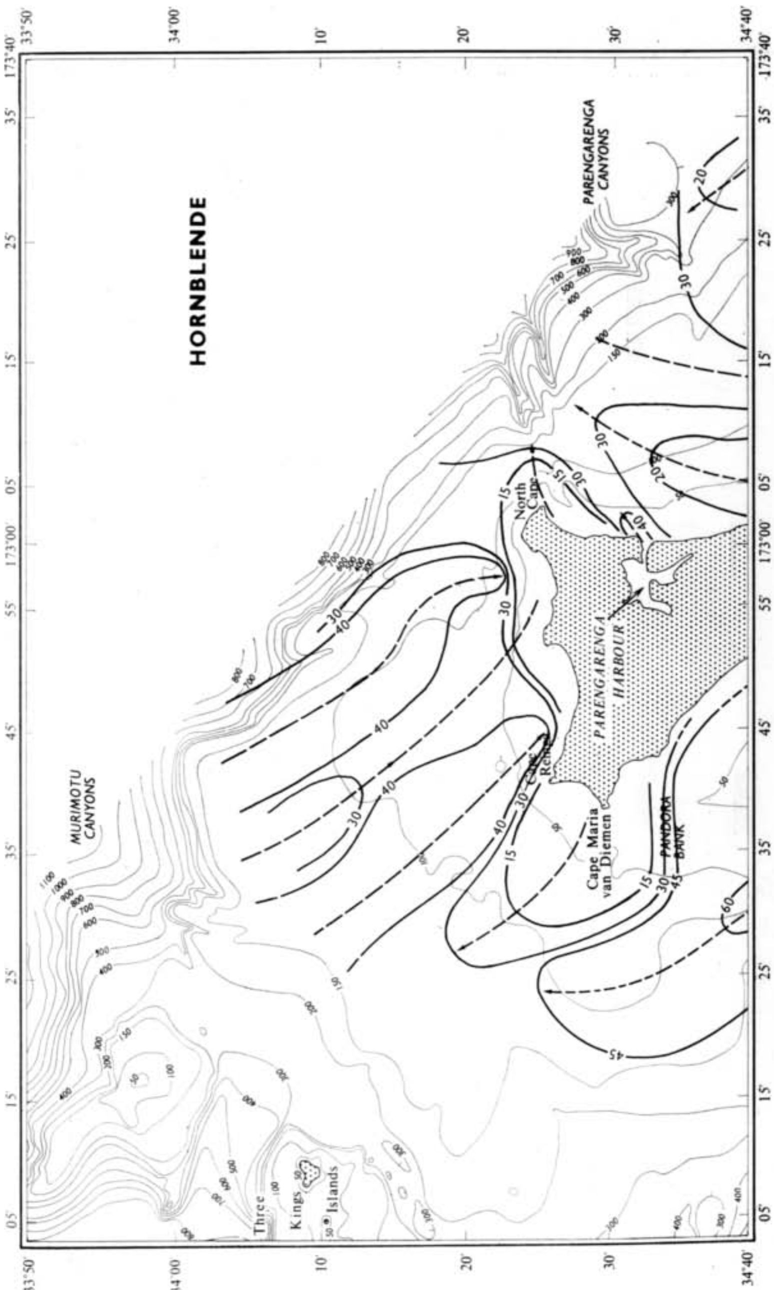


FIG. 13 A–D—Geographical distribution of heavy minerals; B = Hornblende. Total values are contoured and distributional vectors (broken lines) are erected along axes of contour salients (*see* text for discussion).

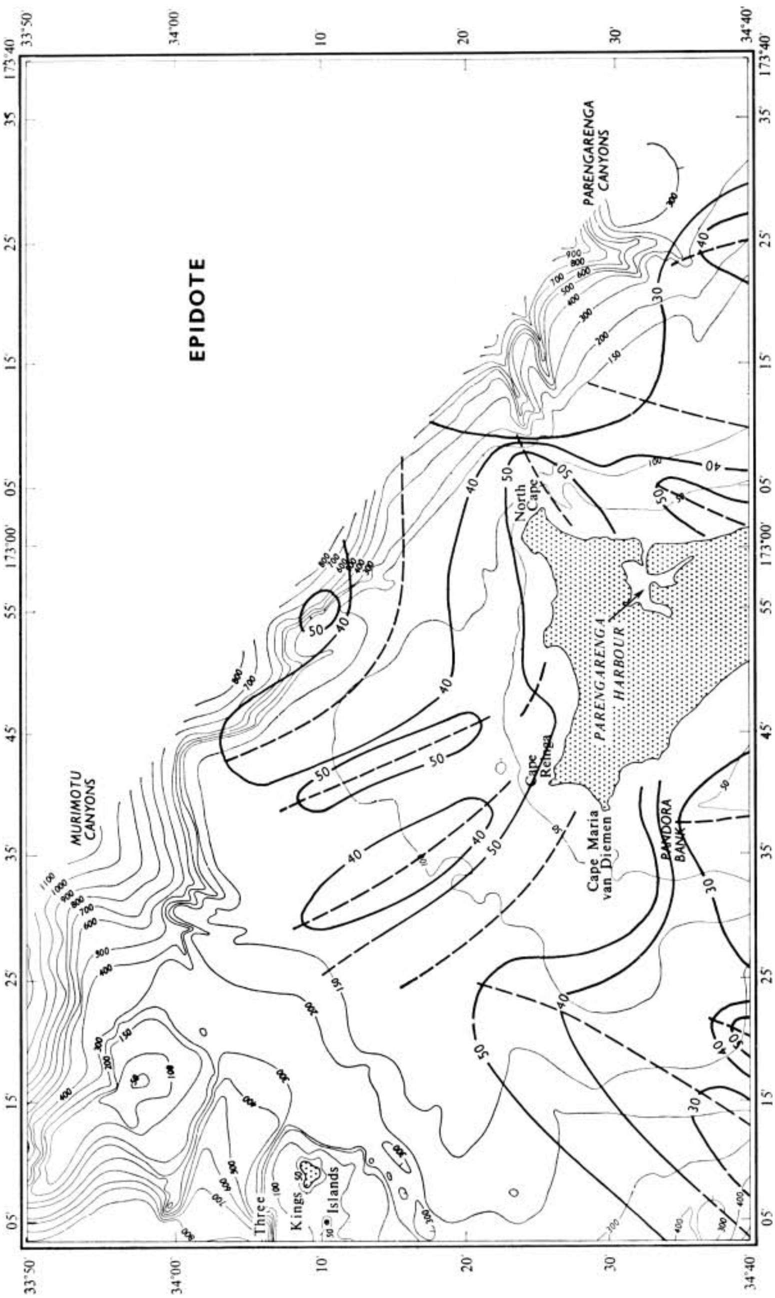


FIG. 13 A–D—Geographical distribution of heavy minerals; C = Epidote. Total values are contoured and distributional vectors (broken lines) are erected along axes of contour salients (*see* text for discussion).

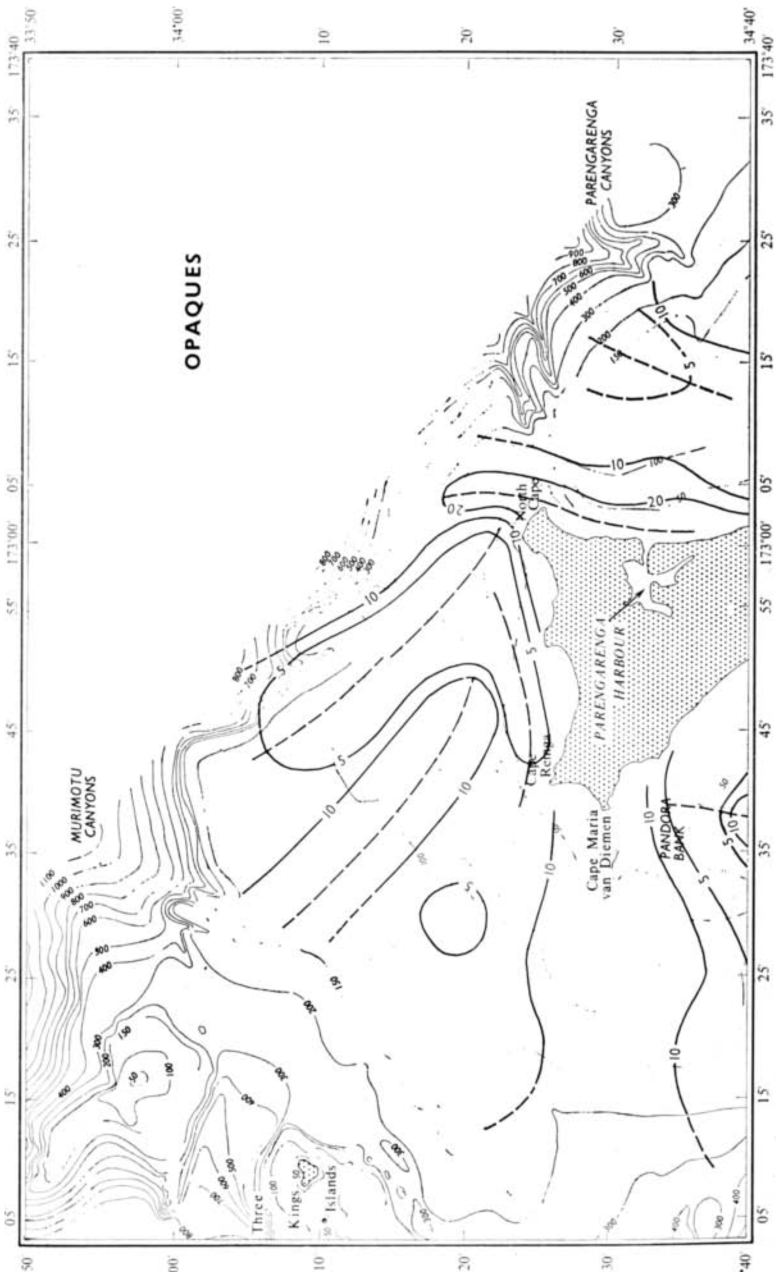


FIG. 13 A–D—Geographical distribution of heavy minerals; D = Opaques. Total values are contoured and distributional vectors (broken lines) are erected along axes of contour salients (*see* text for discussion).

INTERPRETATION

In the foregoing section the continental shelf sediments have been described in terms of some of their textural and mineralogical characteristics and dispersion patterns have been deduced from some of these data. An attempt can now be made to evaluate the general sedimentation pattern in terms of the provenance of mineral species, directions of sediment dispersal, and observed facies distribution.

Provenance

We are dealing here with a pyroxene–opaque - rich and hornblende–epidote - poor eastern province and a western province with a less well defined mineralogy which is generally hornblende–epidote - rich and pyroxene–opaque - poor (Fig. 11). Cursory examination also shows that these provinces contain distinctive light mineral assemblages, the eastern sediments being quartzose, the western quartzo-feldspathic. As quartzose sediments are regarded as more mature than quartzo-feldspathic (Pettijohn, 1957), the possibility that the observed heavy mineral differences could be controlled or influenced by weathering and degree of maturity cannot be excluded. Pettijohn shows hornblende to be more stable than pyroxene, and one would expect the hornblende/pyroxene ratio to increase with maturity. In fact, this ratio is highest in the western or least mature province. Again, epidote is a very stable mineral which is commonly found to be enriched in mature sediments. Here, highest epidote concentrations are found in the sediments of the western province. Evidently then, the differences between heavy mineral assemblages in eastern and western provinces cannot be caused by the degree of maturity but must reflect different provenance. The pyroxene–opaque - rich eastern province assemblage is probably basaltic in origin and may have been derived from the widespread local Tangihua volcanics of Mesozoic age. In contrast the hornblende–epidote - rich western assemblage is probably derived in the main from an andesitic source—probably the Tertiary andesitic rocks common to much of the North Island and found locally, for example, in the Kaurohoupo Conglomerate (*see* Leitch, 1966). Where Cretaceous basalts crop out at Cape Reinga, an eastern province assemblage is found (Fig. 11), which tends to support the above arguments. Similar Cretaceous basalts are known to crop out locally on the shelf around the cape (Summerhayes, in press, a) and yet do not seem to have widely influenced sediment composition. Sediment derived from these rocks during times of lowered sea level may, however, have been more recently buried by movement of sediment derived from a western province source. The occurrence of two zones of hornblende concentration, one on the northern and one on the western shelf (Fig. 13B), suggests that two geographically distinct but geologically similar sources exist here for western province sediments and that these sources are locally more important than the submerged basalts due west of Cape Reinga.

Provenance of sediments south of Cape Reinga is obscure but, assuming that the sands of Ninety Mile Beach are of the same composition over its whole length, these sediments may be derived from as far away as Kaitaia (Fig. 14). The coastal profile of the west of the North Island of New

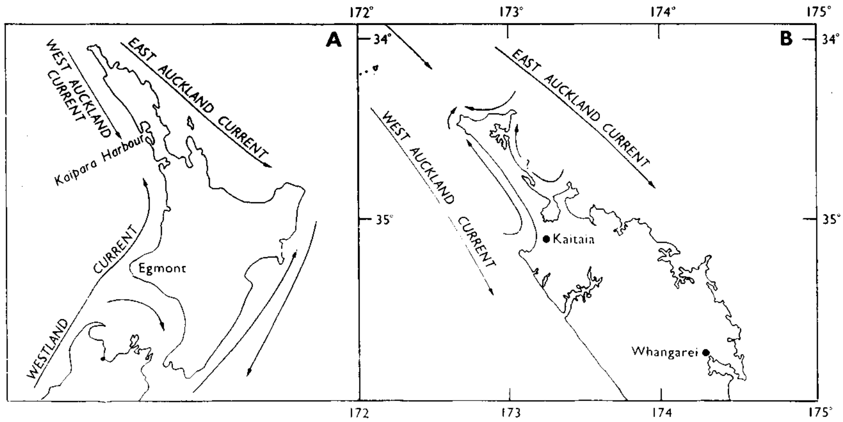


FIG. 14—A. Basic off-shore current pattern round the North Island, New Zealand (*based on* Brodie, 1960).
B. Longshore current activity round northernmost New Zealand deduced from beach texture and coastal profile studies.

Zealand north of Egmont (Fig. 14A) suggests that northward longshore drift prevails here. This observation is in part supported by the observed distribution of off shore and beach ironsand concentrates presumed to be derived by weathering of the andesitic terrain in the western North Island (McDougall, 1960; Kear, 1965). Thus the source of the western province sediments could be a considerable distance south of their depositional area. Deductions made above concerning longshore drift directions conflict with the known coastal current pattern (Fig. 14). The West Auckland Current streams south off shore from Cape Reinga as far south as Kaipara Harbour (Brodie, 1960; Garner, 1961). The rather poorly defined West Auckland Current, found well off shore, does not control the longshore drift which is a fine-scale feature of this environment (Fig. 14).

Sediment Dispersal

As shown in an earlier section, sediment distribution vectors can be established from the regional pattern of mineral concentration and can in certain instances be used to indicate the direction of transporting currents. Modification of mineral concentration by grain size dependence in certain minerals does not allow transport directions to be defined except for hornblende (Fig. 13B). A composite dispersal chart (Fig. 15) incorporating hornblende directional indicators gives a network of distributional vectors from which the influence of currents on sediment distribution may be assessed.

On the western shelf, movement is mainly north to north-west, parallel to the coast. There is some evidence for an eastward swing of currents around Cape Reinga, and across the northern shelf movements are dominantly south-east. This easterly component is substantiated by drift card

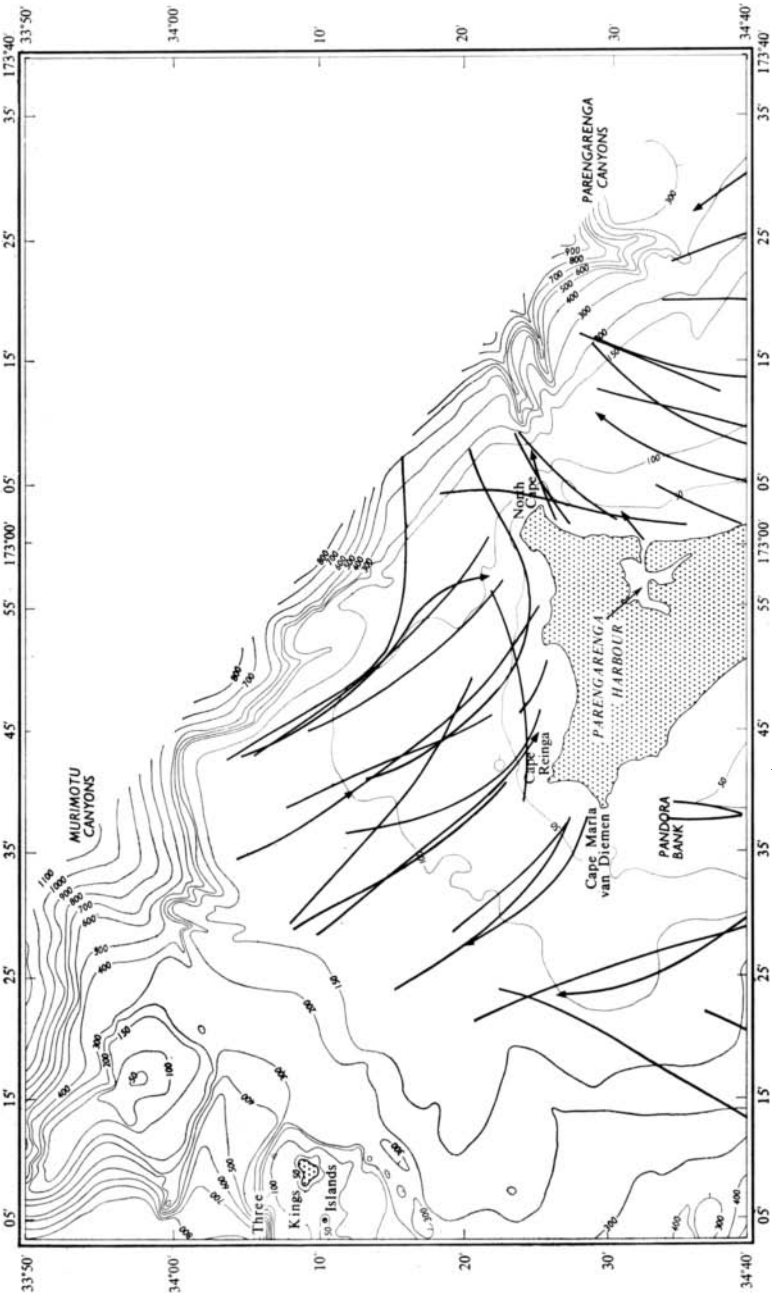


FIG. 15—Composite dispersal diagram containing all distributional vectors from Fig. 13. Arrows represent directions of transport. These movement patterns are "fossil" where they occur outside the zone of presently active sediment movement.

dispersion (*see* Garner, 1961, fig. 30). In fairly shallow water north of North Cape there appears to be an east–west current system which, on evidence from coastal profiles and beach sand textures, seems to be directed to the west. On the eastern shelf, distributional vectors again parallel the coast. Data for hornblende seem to indicate a northward transport direction. This is supported by the positioning of the North Cape Canyons which here come to within 2 miles of the coast and seem to indicate northward movement of currents which are deflected eastward as they approach the cape. Coastal profiles do not indicate any dominant longshore drift direction, which suggests currents here are much weaker than on the northern and western shelves, a conclusion supported by the local occurrence of muddy sediments. Off shore, the prevailing East Auckland Current moves south-eastwards (Fig. 14), but as in the case of the West Auckland Current, we are considering fine-scale current activity which will not necessarily reflect dominant off-shore components. Again it may reasonably be suggested that the sediment transporting currents are eddies derived from the main East Auckland Current but locally moving in the opposite direction to it (Fig. 14).

Some sediment from the eastern province may be moved north around North Cape by strong tidal currents which sweep the sea floor off the cape clear of sediment cover (Summerhayes, in press, a). Because the North Cape Canyon is sited across the path of northward-moving sediment, most of this material will be trapped in the canyon system and will never reach the northern shelf. The occurrence north of North Cape, of eastern province sediment on the outer shelf terrace (Summerhayes, in press, a) in 120 m and greater depths (Fig. 11) therefore requires some different explanation. It is considered that this is a relict sediment body (for reasons given later) deposited at some time of lowered sea level at which time the North Cape Canyons might not have cut across the path of sediment movement; alternatively the sediment could have been derived by the erosion of local and now submerged basaltic rocks again at some time of lowered sea level.

In summary, the directions of sediment movement at the time of deposition can be deduced from the distribution of heavy minerals. A composite dispersal pattern (Fig. 15) reveals a definite, orderly pattern of sediment transport in this region. The pattern is relict because sediment movement is generally not now active at depths greater than about 40 m.

Facies Distribution

Sediment textural characteristics are combined with carbonate ($CaCO_3$) values, representing the contribution of biogenic debris, to produce a facies map of the region (Fig. 5). As discussed above, the texture may be controlled by prevailing hydrodynamic conditions at time of deposition but may also be biased by the local relative availability of calcareous material or detrital clastic sediment. Consequently the $CaCO_3$ content may relate both to environmental energy and the rate of supply of this and other material. An attempt will now be made to resolve this complexity and to unravel the sedimentation history in terms of the facies distribution observed.

Where the authigenic mineral glauconite occurs (*see* Fig. 9) it is assumed that sedimentation is slow or negligible (Cloud, 1955; Norris, 1964). Textural characteristics of glauconitic sediments may not necessarily relate to the present-day environmental conditions but do reflect environmental conditions prevalent during deposition of those sediments.

Eastern Shelf

(1) *Inner sand belt.* Active sediment movement, probably with a northward component, is occurring in the nearshore zone shoaler than 40 m. Much of this sediment may eventually be trapped by the North Cape Canyon system which locally comes to within 2 miles of the shore. Well sorted fine sands occur as deep as 100 m, but it cannot be assumed that the energy conditions of the inshore shallow water region extend to this depth. In fact the presence of glauconite below 40 m indicates that active sediment movement is not occurring below this depth. This suggests that the sands here were deposited in shallow water during some period of lowered sea level. That these sands are not highly calcareous may result either from lack of a local source of calcareous material or from the lapse of time since their deposition being insufficient to allow extensive accumulation of calcareous material.

(2) *Mid-shelf muddy calcarenites.* Prevalence of muddy sediments at mid-shelf depths indicates seaward weakening of the prevailing coastal current system. The occurrence of glauconite suggests that the sedimentation rate is very slow; the higher carbonate percentage (Fig. 6) suggests the lapse of considerable time since this area was one of active detrital sedimentation.

(3) *Outer fine sand belt.* The slightly calcareous fine sands of the outer shelf are texturally and mineralogically similar to those found in shallow water at the present and they may have been deposited under similar energy conditions in shallow water at some time of lowered sea level. The possibility that these sediments could have been derived by seaward movement from shallower water is most unlikely since they are separated from the inshore fine sands by a low energy environment where muds are deposited. That active sedimentation is not occurring here is shown by the presence of glauconite. The local decrease in carbonate towards the shelf edge is possibly induced by the winnowing action of a zone of strong currents near the shelf edge. That such currents occur near the shelf edge is well documented (Sverdrup *et al.*, 1942; Kuenen, 1950; Shepard, 1963) and since the major carbonate component at this depth is likely to be foraminiferal, winnowing would be an effective separation mechanism. These sediments are very well sorted reflecting good adjustment to prevailing energy conditions.

Northern Shelf

Below 100 m is a zone of glauconitic calcarenite where detrital sedimentation is negligible and the detrital component is probably relict. Carbonate values near the shelf edge, particularly in the north, are slightly lower than values in adjacent shelf sediments and, as for the eastern shelf, this may be a zone where the fine calcareous component is winnowed out by current activity. Texturally and mineralogically these sands resemble those from the high energy inshore environments in this region and it is suggested that they were formed under similar conditions at times of lowered sea level, although the correlation with inshore sediments is less readily apparent than for the eastern shelf sediments. Sorting in these outer shelf sediments again is very good indicating good adjustment to prevailing energy conditions at the shelf edge.

Above 100 m calcarenites predominate in the west and detrital sediments in the cast; neither is glauconitic and it is inferred that present-day sediment movement is occurring here. The biogenic debris constituting the calcareous fraction of the calcarenites is most probably derived from the rocky region of coarse calcarenite west of Cape Reinga. The distribution of biogenic debris parallels the distribution patterns deduced from heavy mineral studies. Weakening of the currents away from the cape may explain why this material does not cover the whole region. The control may, however, be topographic because the slight ridge extending north from Spirits Bay would tend to obstruct any easterly moving sediment body. The derivation of the relatively non-calcareous detrital sands of the eastern region is obscure but they are mineralogically and texturally similar to local shallow water sands. They may thus have been derived by the erosion of originally shallow water sands deposited on the shelf at times of lowered sea level. Since there are no streams of any significant size draining the adjacent land mass, their source cannot be the emergent part of New Zealand. Also, sediment dispersal patterns deduced from heavy-mineral studies (Fig. 15) suggest that these sediments are moving toward the coast, not away from it. The lack of calcareous material may be an effect of (a) the topographic barrier discussed above, (b) the winnowing of foraminiferal calcareous remains, or (c) the lack of any large local source of calcareous material.

In shallow water near the coast, sediment distribution is complex and probably controlled both by easterly currents rounding Cape Reinga and westerly currents rounding North Cape (*see* previous section on sediment dispersal, p. 199). Locally, this off-shore complexity gives rise to composite beach sands presumably because, during storms, sediments may be washed shoreward from different directions.

Western Shelf

The western shelf may be conveniently divided into a coarse calcarenite facies extending west from Cape Reinga, and a fine-medium detrital sand facies which covers the shelf to the south. The coarse calcarenites occur in a region where the sea floor is rocky and the local supply of detrital sediment is negligible. Northward migration of sediment from the south is blocked by the low westerly trending ridge on which the calcarenites occur. The local occurrence of glauconitic calcarenite signifies slow sedimentation. Presence of boulders and exposures of bedrock shows the sediment cover to be thin; it also reflects the locally increased current activity which transports some of the calcareous material north-east.

South, among the very well sorted fine and medium sands, glauconite is found below 100 m; above this depth, sediment movement is probably actively occurring. Once again, the textural and mineralogical similarity of these deep sands to those in the active sedimentation zone suggests that they were originally deposited in a similar high energy environment probably near a lowered sea level. Present current activity may be adequate to mechanically winnow out the fine foraminiferal detritus which might otherwise settle here.

In less than 100 m depth, parallel zones of fine, very well sorted sand occur in the highest energy environments along the shore and on the Pandora Bank. In the adjacent lower energy environments, medium sands occur and, locally, very sandy muds. Sediment dispersal patterns outlined in the section beginning on p. 199 indicate a dominantly northward component of sediment transport. Probably the most active transport occurs in the fine sand zones. To the north the low ridge west of Cape Reinga serves to deflect the sediment load west; in the past this may have contributed to the formation of canyons cutting the shelf edge.

Sediments of the Maria Ridge

The coarse and medium, poorly sorted calcarenites of the Maria Ridge system are composed chiefly of bryozoan debris with an increased molluscan component in shallow water. Glauconite is only found in a few samples which may indicate that sedimentation is quite rapid over most of the region. However, it may also be that in a dominantly calcareous environment the physico-chemical conditions required for glauconite formation are lacking. Biological productivity in this area is likely to be high in view of the presence of upwelling currents (Garner, 1961) which are commonly enriched in nutrients (Sverdrup *et al.*, 1942; Brongersma-Sanders, 1957). Thus a high sedimentation rate of calcareous material may explain the absence of glauconite.

On the Three Kings shelf and the van Diemen and Bowling Banks, which were all produced by marine erosion during the Pleistocene (Summerhayes, in press, a), sedimentation is slow, as evinced by the formation of large algal concretions around pebbles and boulders on the banks and the widespread occurrence of boulders and bedrock outcrops on both the banks and the shelf. Similar calcareous algal balls composed of many concentric layers are found on the Challenger Bank off Bermuda (Stetson, 1953) and on the Flower Garden Banks in the Gulf of Mexico (Parker and Curray, 1956).

In summary, certain conclusions can be drawn regarding the sedimentation history of this region. A nearshore zone of fine well sorted sand, relatively low in carbonate and without any glauconite, defines the region of presently active sedimentation. On the outer shelf are relict sands originally deposited in shallow water and preserved mainly because of winnowing by shelf edge current activity. At mid-shelf depths similar sands occur locally although calcarenites and muds are also found and facies distribution is generally rather complex. Most of the detrital shelf sediments seem to be relict deposits formed originally in shallow water high energy environments probably during the post-glacial sea level rise of the last 20,000 years. Locally, highly calcareous material accumulates slowly, with glauconite, in environments in which detrital sedimentation or active sediment movement is not apparent. An exception to this on the continental shelf is the zone of coarse calcarenite off Cape Reinga where there is a ready source of carbonate material and no local detrital source.

The interpretation of the majority of these shelf sediments as transgressive shallow water sands is in keeping with findings of many other investigations in other parts of the world (*see* Shepard, 1963, 1964; Emery, 1952, 1965; van Andel, 1964, 1965; Curray, 1960, 1961; and others).

CONCLUSIONS

1. Shelf sediments round northernmost New Zealand are most probably relict shallow water deposits formed at or near low stands of sea level during the last 20,000 years.

2. The transport directions which prevailed in the fossil depositional environments occur in the nearshore environment at present.

3. An eastern heavy mineral province has a southern basaltic provenance; a western heavy mineral province has a southern and local andesitic provenance. Because the eastern province sediments are quartzose, they are more mature than the quartzo-feldspathic western province sediments.

4. Mineralogical differences between the heavy minerals of these provinces are not governed by differences in age or grain size.

5. Glauconite is forming in microenvironments such as the tests of foraminifers over much of the area in depths greater than 40 m. This shows that . . .

6. . . . sedimentation is not now actively proceeding except in shallow water near the coast and in restricted zones of deeper water.

7. The presence of extensive calcarenite is in part a function of the slowness of non-carbonate detrital clastic sedimentation and in part a function of the high local biological productivity of surface waters caused by upwelling phenomena. Where active sediment movement is occurring in the nearshore zone, carbonate sedimentation is low.

8. Intensified current activity at the shelf edge is thought to inhibit deposition of fine-grained calcareous skeletal debris and result in local lowering of carbonate values.

9. The extensive accumulations of calcarenite on Maria Ridge are caused by high local biological productivity and the absence of any local source of detrital clastic material.

10. Extensive accumulation of algal layers around basalt pebble nuclei on van Diemen and Bowling Banks indicates that sedimentation on these banks has been extremely slow since the bank tops were terraced by marine erosion during the Pleistocene.

ACKNOWLEDGMENTS

This paper was initiated under the guidance of Mr J. W. Brodie, New Zealand Oceanographic Institute (N.Z.O.I.), to whom I owe sincere thanks for encouragement during preparation of the manuscript. Dr H. M. Pantin and Dr W. J. M. van der Linden of the same institute offered valuable assistance and discussion during data processing. My thanks are also extended to Dr G. Evans and Dr P. Bush (Geology

Department, Imperial College) for their criticism of the manuscript. For assistance in sample collection I am indebted to the Master and crew of m.v. *Taranui* and to Dr W. J. M. van der Linden, Mr J. G. Gibb, and Mr N. M. Ridgway of N.Z.O.I. and Mr W. F. Ponder of Auckland University. I am also grateful to the Cape Reinga lighthouse keepers and my wife, Lesley, for assistance during beach sampling. Samples were ably prepared by Mr I. D. Slater, Miss C. M. Jenkins, and Mr R. Titcombe; drafting was done by Miss P. Lawrence of N.Z.O.I., and Cartographic Section, Information Service, Department of Scientific and Industrial Research, Wellington, under the supervision of Mr C. T. T. Webb.

REFERENCES

BRODIE, J. W. 1960: Coastal surface currents around New Zealand. *N.Z. Jl Geol. Geophys. 3*: 235–52.

BRONGERSMA-SANDERS, M. 1957: Mass mortality in the sea. *In*: "Treatise on Marine Ecology and Palaeoecology". *Mem. Geol. Soc. Am. 67 (1)*: 941–1010.

CLOUD, P. E. 1955: Physical limits of glauconite formation. *Bull. Am. Ass. Petrol. Geol. 39*: 484–92.

COTTON, C. A. 1951: Accidents and interruptions in the cycle of marine erosion. *Geogr. Jl 107*: 343–9.

CREAGER, J. S. 1963: Sedimentation in a high energy, embayed, continental shelf environment. *J. sedim. Petrol. 33*: 815–30.

CULLEN, D. J. 1966: A series of coloured charts of New Zealand coastal sediments. *Inf. Ser. N.Z. Dep. scient. ind. Res. 56*: 3–11.

CURRAY, J. R. 1960: Sediments and history of the Holocene transgression, continental shelf, northwest Gulf of Mexico. *In* SHEPARD *et al.*: "Sediments of the Northern Gulf of Mexico". *Spec. Publ. Am. Ass. Petrol. Geol.*: 221–66.

——— 1961: Tracing sediment masses by grain size modes. *Int. geol. Congr. 21*: 119–30.

EMERY, K. O. 1952: Continental shelf sediments of Southern California. *Bull. geol. Soc. Am. 63*: 1105–8.

——— 1965: Geology of the continental margin off eastern United States. *In* WHITTARD, W. F.; BRADSHAW, R. (Eds.): "Submarine Geology and Geophysics". Proc. 17th Sympos. Colston Research Soc., Bristol. Butterworths, London. Pp. 1–20.

FOLK, R. L.; WARD, W. C. 1957: Brazos River Bar: a study in the significance of grain size parameters. *J. sedim. Petrol. 27*: 3–26.

GARNER, D. M. 1961: Hydrology of New Zealand coastal waters, 1955. *Bull. N.Z. Dep. scient. ind. Res. 138 (Mem. N.Z. Oceanogr. Inst. 8).* 85 pp.

INMAN, D. L. 1952: Measures for describing the size distribution of sediments. *J. sedim. Petrol. 22*: 125–45.

KEAR, D. 1965: Geology of New Zealand's ironsand resources. Paper 219. *Eighth Commonw. Min. Metall. Congr.*: 1–10.

KEAR, D.; HAY, R. F. 1961: Sheet 1—North Cape. "Geological Map of New Zealand 1 : 250,000". New Zealand Department of Scientific and Industrial Research, Wellington.

KUENEN, PH. H. 1950: "Marine Geology". John Wiley, New York. 568 pp.

LEITCH, E. 1966: Geology of the North Cape area, northernmost New Zealand. (Thesis lodged in Auckland University Library.)

MCDOUGALL, J. C. 1960: Ironsand deposits offshore from the west coast, North Island, New Zealand. *N.Z. Jl Geol. Geophys. 3*: 283–300.

MOORE, J. R. 1968: Recent sedimentation in northern Cardigan Bay, Wales. *Bull. Br. Mus. nat. Hist., Mineralogy, 2.* 131 pp.

Norris, R. M. 1964: Sediments of Chatham Rise. *Bull. N.Z. Dep. scient. ind. Res. 159 (Mem. N.Z. oceanogr. Inst. 26).* 40 pp.

Pantin, H. M. 1966: Sedimentation in Hawke Bay. *Bull. N.Z. Dep. scient. ind. Res. 171 (Mem. N.Z. oceanogr. Inst. 28).* 70 pp.

Parker, R. H.; Curray, J. R. 1956: Fauna and bathymetry of banks on continental shelf, northwestern Gulf of Mexico. *Bull. Am. Ass. Petrol. Geol. 40*: 2428–39.

Pettijohn, F. J. 1957: "Sedimentary Rocks", 2nd edn. Harper, New York. 718 pp.

Seed, D. P. 1968: The analysis of the clay content of some glauconitic oceanic sediments. *J. sedim. Petrol. 38 (1)*: 229–31.

Shepard, F. P. 1963: "Submarine Geology", 2nd edn. Harper and Row, New York. 557 pp.

——— 1964: Criteria in modern sediments useful in recognising ancient sedimentary environments. *In* Van Straaten, L. M. J. U. (Ed.): "Developments in Sedimentology", Vol. 1 "Deltaic and Shallow Marine Deposits". Elsevier, Amsterdam. Pp. 1–25.

Shepard, F. P.; Moore, D. G. 1955: Central Texas coast sedimentation: characteristics of sedimentary environment, recent history and diagenesis. *Bull. Am. Ass. Petrol. Geol. 39 (8)*: 1463–593.

Spencer, D. W. 1963: The interpretation of grain size distribution curves of clastic sediments. *J. sedim. Petrol. 33*: 180–90.

Stetson, H. C. 1953: The sediments of the western Gulf of Mexico. Part I—The continental terrace of the western Gulf of Mexico: its surface sediments, origin and development. *Pap. phys. Oceanogr. Met. 12.* 45 pp.

Summerhayes, C. P. in press a: Submarine geology and geomorphology off northern New Zealand. *N.Z. Jl Geol. Geophys. 12 (2).*

——— in press b: Marine geology of the New Zealand Subantarctic sea floor. *Bull. N.Z. Dep. scient. ind. Res. (Mem. N.Z. oceanogr. Inst.)*

Sverdrup, H. U.; Johnson, M. W.; Fleming, R. H. 1942: "The Oceans". Prentice-Hall, New York.

van Andel, Tj. H. 1964: Recent marine sediments of the Gulf of California. *In* van Andel, Tj. H.; Shor, G. G.: "Marine Geology of the Gulf of California". *Mem. Assoc. Petrol. Geol. 3*: 216–311.

——— 1965: Morphology of sediments of the Sahul Shelf, Northwestern Australia. *Trans. New York Acad. Sci., ser. 2, 28*: 81–9.

van der Linden, W. J. M. 1967: A textural analysis of Wellington Harbour sediments. *N.Z. Jl Mar. Freshwat. Res. 1*: 26–37.