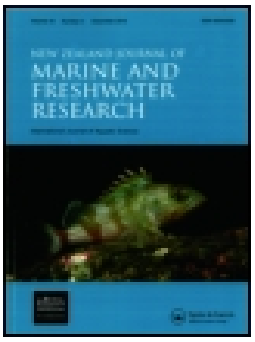

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Surficial sediments of Raglan Harbour

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Raglan Harbour, a drowned river valley system lying in a structurally depressed fault-block, has a maximum depth of 18 m and covers about 33 km^2, 70% of which consists of tidal flats up to 1 km wide and dissected by channels up to 5 m deep. Salinities range mainly from 30 to 33‰, and truly estuarine conditions are restricted to the tidal reaches of small streams entering the harbour.

Sediments range from clean, well sorted sands in the beaches, dunes, channels, and bars in the lower harbour to mainly muddy sands, sandy muds, and muds in the extensive tidal flats of the middle and upper harbour. Gravelly sediments occur sporadically as the product of shore line erosion, and as lag and dump deposits in channels. Sediment transport and deposition is primarily under the control of cyclically variable, multidirectional tidal flows, complicated by a complex bottom topography. Tidal currents attain surface speeds of 50–150 $cm.s^{-1}$ and effect mainly a net seaward drift of suspended sediment but a net up-harbour transport of bed-load material.

Harbour sediments consist of quartz, feldspar, and clay minerals supplied by streams and by shore line erosion from hinterland Mesozoic to Quaternary sedimentary and volcanic rocks; of titanomagnetic and ferromagnesian minerals derived mainly from coastal ironsands by wind, wave, and current action; and of skeletal aragonite and calcite supplied by an intrabasinal, predominantly molluscan benthos. Subrecent to Recent diagenetic phosphatic concretions occur locally in the harbour.

A large proportion of the tidal flats in Raglan Harbour are simply sediment-covered rock platforms formed by active erosion by wetting and drying of coast line montmorillonitic mudstones; cliff recession rates of about 2 $cm.y^{-1}$ are indicated. Only a thin veneer of sediment covers the modern shore platform which is up to 100 m wide and has been cut during the last 5000 years, since when Raglan Harbour has acted mainly as a sediment trap. A −10 m platform beneath the tidal flats is up to 600 m wide and was eroded during an interstadial sea level stand, possibly from 85 000 to 60 000 years ago, with contemporaneous deposition of the montmorillonite-dominated detritus on the continental shelf.

INTRODUCTION

Raglan Harbour is the most northerly of three adjacent harbours of generally similar physiography on the west coast of central North Island (Figs 1–3). The harbour covers about 33 km^2 of which 24 km^2 is intertidal, and has formed by the post-glacial (Aranuian) drowning of the lower part of a branching river system carved in a structurally depressed block produced by southwest trending faulting and associated down-warping in the Upper Miocene (Chappell 1970). The narrow harbour entrance is flanked by blacksand beaches backed by extensive, unvegetated dunes to the north (the Nukumiti Sands Member of Pain (1976)) and the andesitic cone of Mt Karioi to the south.

The geology of the drainage basin (165 km^2) is dominated by indurated Mesozoic sandstones and mudstones in the east, by soft calcareous mudstones and muddy fine sandstones of the Oligocene Te Kuiti Group in the north, and by andesites and basalts of the Upper Pliocene–Lower Pleistocene Alexandra Volcanics in the south. Quaternary volcanic ashes thinly mantle much of the area (Henderson & Grange 1926, Kear 1960, 1966, Pain 1975). Most of the 90 km of shore line to Raglan Harbour consists of readily erodible mudstones of the Te Kuiti Group which commonly form extensive shore platforms.

This study documents the texture and composition of the surficial sediments of Raglan Harbour and attempts to interpret these properties in terms of provenance and mechanisms of sediment transport and deposition. For ease of reference in the text the harbour is divided into four areas: lower, middle, north upper, and south upper (Fig. 1).

METHODS

Ninety-five samples were collected for laboratory analysis (Fig. 4). Bottom sediments were collected from a boat using a 500 ml capacity Marukawa grab sampler. Beach and dune samples were scooped from the top 5 cm of sediment surface.

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Current speeds, water salinities, and suspended sediment concentrations were determined at 30 min intervals on 1 March 1979 over a spring tidal cycle at a single hydrologic station in the lower harbour (Fig. 4). Measurements were made 1 m above bottom, at mid-depth, and 1 m below surface. Flows were measured with a Gurley current meter and salinities with a probe-type Model 33 S-C-T Yellow Springs salinometer. Water samples were collected with a Nansen reversing bottle and their suspended sediments concentrated on 0.45 μm mesh millipore filters for weighing.

In the laboratory the weight percent of calcium carbonate and of organic matter in samples was determined by digestion in 4.4 M acetic acid and 20 vol. hydrogen peroxide respectively. After acid digestion, samples were washed several times and wet sieved through a 4ϕ (0.063 mm) screen to separate the mud from the sand and gravel fractions. The pipette method was used to determine the weight

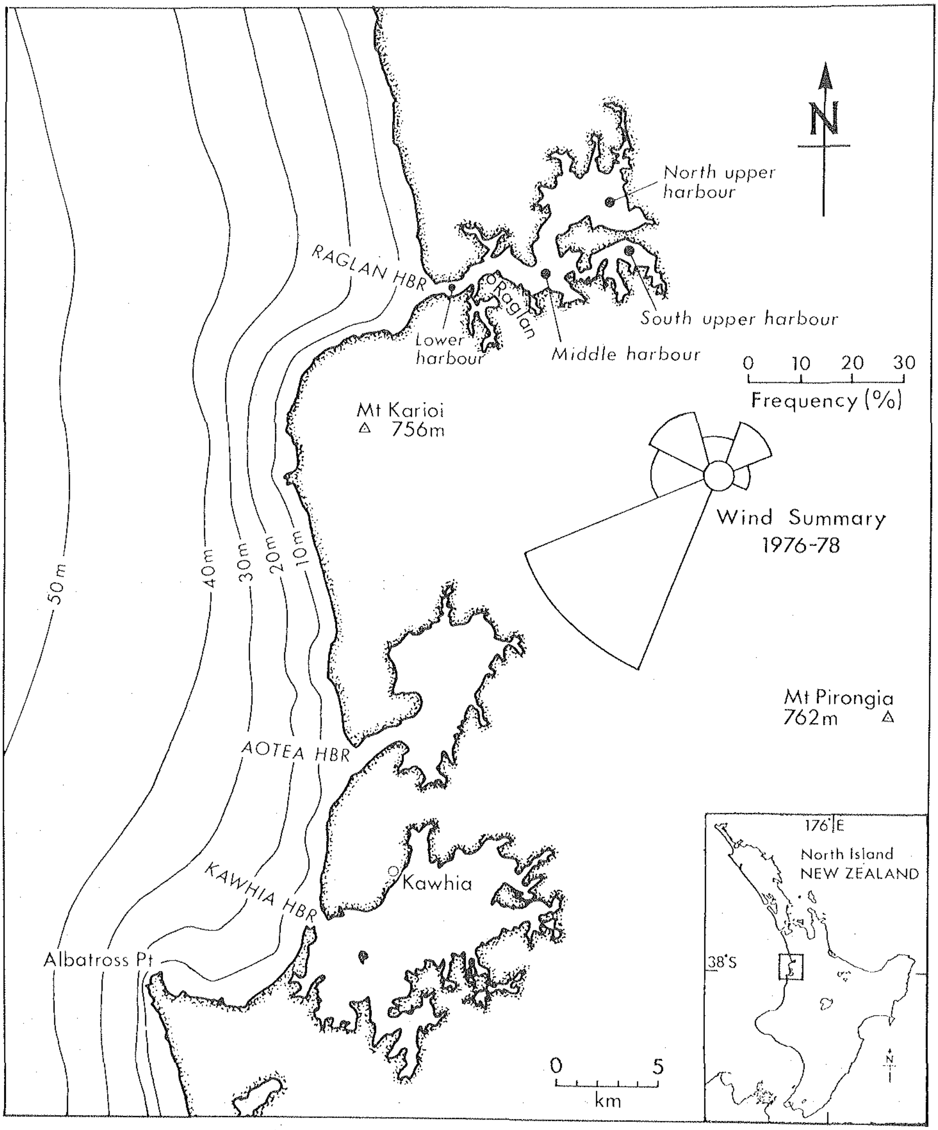


Fig. 1. Raglan Harbour showing informally named areas within the harbour, off-shore bathymetry after McDougall & Brodie (1967), and wind summary for Te Mata, 10 km south of Raglan (data supplied by N.Z. Meteorological Service).

Fig. 2. Oblique aerial view at high tide looking north-east up Raglan Harbour showing a part of the lower harbour at left, the middle harbour immediately beyond Raglan township, and the north and south upper harbours in the distance at left and right respectively. Several low cliffs of Oligocene mudstone are seen about the shore line and the distant hills consist mainly of Mesozoic sandstone and siltstone.

Photograph supplied by Whites Aviation.

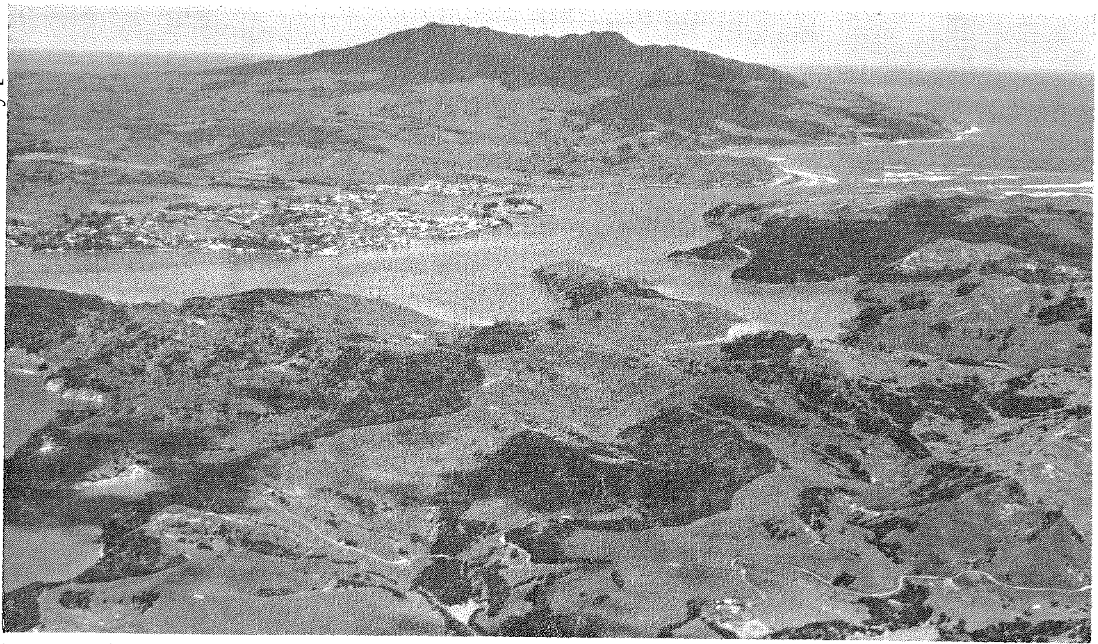


Fig. 3. Oblique aerial view at high tide looking south-west across the lower harbour towards Raglan township and the andesitic cone of Mt Karioi (756 m). Hills in the foreground are mainly Oligocene mudstone. Note waves breaking over the sand bar outside the harbour entrance and the active lobes of wind-blown sand extending inland over the hills immediately north of the harbour entrance.

Photograph supplied by Whites Aviation.

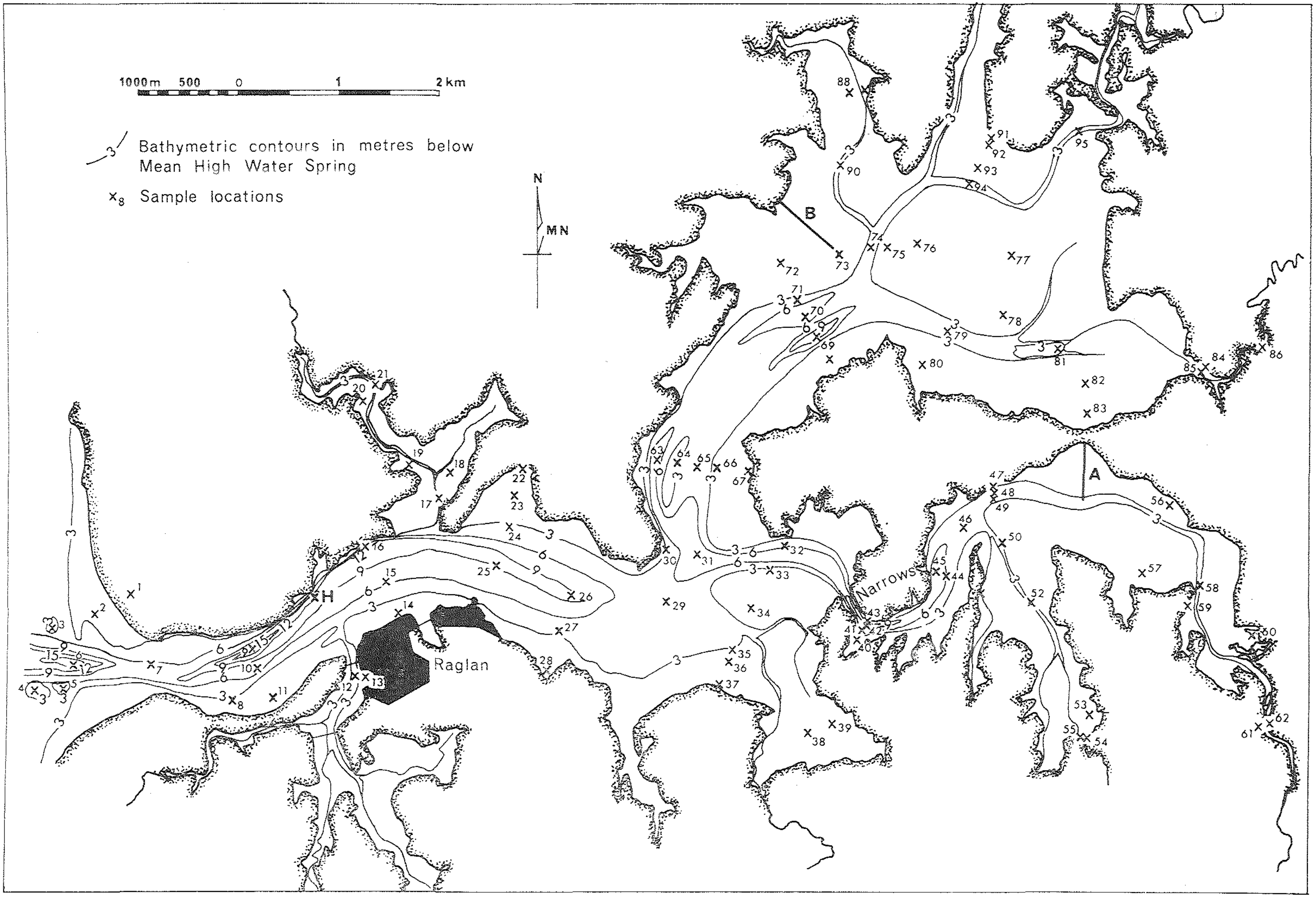


Fig. 4. Generalised bathymetric map of Raglan Harbour showing sample sites, and locations of hydrologic station (H; see Fig. 14) and rock platform profiles (A & B; see Fig. 9). Bathymetry from Admiralty Chart N.Z. 4421 (1962), soundings during field work, and air photograph examination

percent of silt and clay in the mud fraction; the size distribution in this fraction was similarly determined for six samples only.

Sand and gravel fractions for all samples were sieved at $\frac{1}{4}\phi$-intervals in a mechanical sieve shaker for 10 min. A cumulative frequency curve was constructed on probability paper for each sample and the Folk & Ward (1957) graphic size parameters of mean grain size ($Mz\phi$), sorting ($\sigma_1\phi$), skewness (Sk_I), and kurtosis (K_G) for the coarser than 4ϕ fraction were calculated. This unconventional approach to grain size distribution analysis is discussed more fully by Nelson (1977). Essentially, the grain size parameters reported here reflect the size distribution characteristics of only the bed load material in samples, it being this material which best reflects the hydraulic conditions existing at the time of sediment deposition. The relative importance of suspension load transportation can be gauged independently from the amount of mud-sized material in samples. (Tabulated results of all carbonate, organic matter, and textural analyses are available on request.)

Compositional characteristics of Raglan Harbour sediments are based on detailed analysis of 20 samples. Bulk mineralogy was determined by X-ray diffraction analysis using the semi-quantitative procedure of Nelson & Cochrane (1970). The clay mineralogy of the less than 2 μm fraction of oriented particle mounts was determined by standard X-ray diffraction techniques (Carroll 1970) and semi-quantified using the methods of Weaver (1967). The heavy and light minerals in the fine sand fraction (2–3 ϕ) were separated with tetrabromoethane (s.g. = 2.97) in steep-sided funnels, weighed, and their respective percentages determined. Concentrations were microsplit and mounted on slides for petrographic examination and point-counting (av. 300 grains).

BATHYMETRY AND ENVIRONMENTS

Some morphometric and other data for Raglan Harbour are given in Table 1, and a bathymetric map prepared from data on Admiralty Chart N.Z. 4421 (1962), examination of aerial photographs, and soundings made during field work, in Fig. 4. The map defines three depth zones:

1. Regions shallower than 3 m are exposed at mean low water. These intertidal areas occupy about 70% of the harbour and consist mainly of broad tidal flats (Fig. 5), but include sediment bars in the arm connecting the middle and north upper harbour, and ocean beaches at and near the mouth of the lower harbour. Sand flats form the southern margin of the lower harbour, but elsewhere mud flats, consisting of soft, sticky muds, sandy muds, and muddy fine sands, predominate. The apparent lack of inorganic sedimentary structures in tidal flat sediments is mainly the result of reworking by a prolific benthic macrofauna, dominated by molluscs. The bivalve *Chione stuchburyi* and the gastropod *Amphibola crenata* are the dominant species; other important species include the bivalves *Cyclomactra ovata, Leptomya retiaria,* and *Paphirus largillierti,* and the gastropods *Cominella maculosa, C. glandiformis, C. adspersa,* and *Zeacumantus lutulentus.* Several unidentified species of burrowing and sediment-ingesting worms also contribute to sediment reworking.
2. The zone from 3 to 9 m deep includes the bulk of the remainder of the harbour and consists mainly of tidal gullies and channels of highly variable dimensions. Tidal mud flats are drained by a system of meandering runnels, up to several tens of centimetres wide, which may unite as tidal gullies before discharging into the main channels (Fig. 6). The gastropod *Maoricolpus roseus* and the bivalve *Myadora striata* are common additions to the benthic fauna in these deeper waters.
3. Depths greater than 9 m are restricted to the main channel in the lower harbour and to constrictions in the major channels in the upper harbours. The channel near the entrance is flanked by broad ironsand beaches and dunes, and has a permanent offshore bar across its mouth over which waves break continually (Fig. 3).

Thus three major sedimentary environments occur in Raglan Harbour: tidal flat, tidal channel, and a beach-bar-dune complex.

Table 1. Morphometric and other data for Raglan Harbour (cf. Heath 1976).

Climate	
Mean annual air temp. (°c)	13
Mean annual rainfall (mm)	1400
Prevailing wind	SW
Drainage basin	
Area (km²)	165
Max. elevation (m)	756
Mean elevation (m)	125
Harbour characteristics	
Max. length (km)	11
Max. width (km)	6
Entrance width (km)	0.5
Max. depth (m)	18
Mean depth (m)	2.5
Perimeter (km)	90
Harbour area (km²)	33
Tidal flat area (km²)	24
Vol. water at high tide (km³)	0.08
Tidal range	
Spring tides (m)	2.8
Neap tides (m)	1.8
Entrance cross-sectional area	
Low tide spring (m²)	2900
Mid tide spring (m²)	3600
Tidal compartment	
Spring tides (km³)	0.06
Neap tides (km³)	0.04

Salinities in the harbour are only slightly lower than the open ocean, ranging from about 30 to 33‰ (Heath & Shakespeare 1977). Salinity measurements made during current monitoring at station H in the lower harbour (Figs 4 & 14) indicate that the water column here is essentially vertically homogeneous, ranging from 30 to 30.5‰ for an hour or so on either side of low tide, but from 31 to 32‰ over the remainder of the tidal cycle. Truly estuarine conditions are restricted to the most distal reaches of the harbour where sea water is measurably diluted to less than 30‰ by small fresh water streams.

SHORE PLATFORMS

Shore platforms of variable extent occur about much of the harbour margin and are conspicuously developed on southwest facing shore lines cut in Whaingaroa Siltstone and Aotea Sandstone of the Oligocene Te Kuiti Group (Fig. 7). The platforms are backed in places by cliffs up to 35 m high and are covered by a variable thickness of muddy sediment; most of the landward sections of tidal flats are simply sediment-veneered rock platforms extending about 100 m from shore (Figs 8 & 9). Beyond this distance probing with steel rods in the upper harbour shows that the rock platforms drop quickly to about −10 m below mean high water level and extend for distances of 500 m or more across the arms of the harbour (Fig. 9).

The modern shore platforms have been eroded by a combination of weak wave action and subaerial weathering above the zone of permanent water saturation. Where fresh, mudstones and muddy sandstones of the Whaingaroa Siltstone and Aotea Sandstone are fairly hard, massive rocks with a subconchoidal fracture. However, subaerial wetting by wave splash and rain followed by drying causes shore line outcrops to crumble readily because of their exceptionally high content of montmorillonite (Nelson 1973, Nelson & Hume 1977). This is the dominant mechanism in the erosion of mustones during shore platform formation (Healy 1967). Wave action acts mainly as a suspending medium, or causes abrasion between particles and, together with boring organisms, reduces erosional detritus to a sufficiently small size for transportation by tidal currents.

TEXTURE

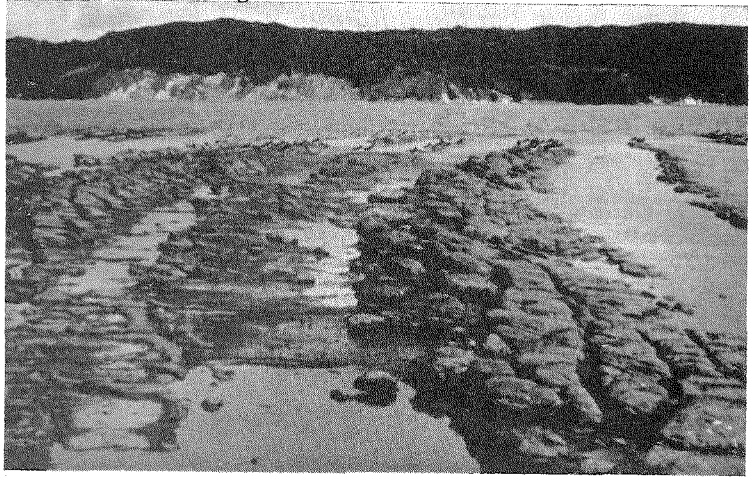
Textural Plots

Sediments of Raglan Harbour include a large number of textural classes (Fig. 10) reflecting a wide range of variables acting on the sediment system. Fig. 11 summarises their distribution; separate isopleth maps showing the weight percent of sand, mud, silt, and clay are available on request.

Scattered gravel-bearing sediments represent lag deposits in areas of vigorous currents, shore line deposits derived from active cliff erosion, or dump deposits at the mouths of streams entering the harbour. Pure sands occur only in the lower harbour and become progressively more muddy up-harbour, passing through regions of muddy sands, sandy muds, and finally muds in distal reaches, reflecting a general up-harbour decrease in energy conditions.

The harbour channel sediments are generally coarser than associated tidal flat sediments, indicating that the strongest currents are mainly confined to channels. However, in the north upper harbour the reverse is often found and the extensive areas of tidal flat sediments contain from 25 to 70% sand compared to less than 25% in the adjacent channel sediments.

Fig. 5. Upper 100 m of intertidal mud flat exposed at mid-tide in the south upper harbour, Raglan Harbour; at low water the flat is over 300 m wide. Note the shore-line cliffs in Whaingaroa Siltstone, the coarse sediment accumulations at the cliff base, and the large population of gastropods (*Amphibola crenata*) on the mud flats.



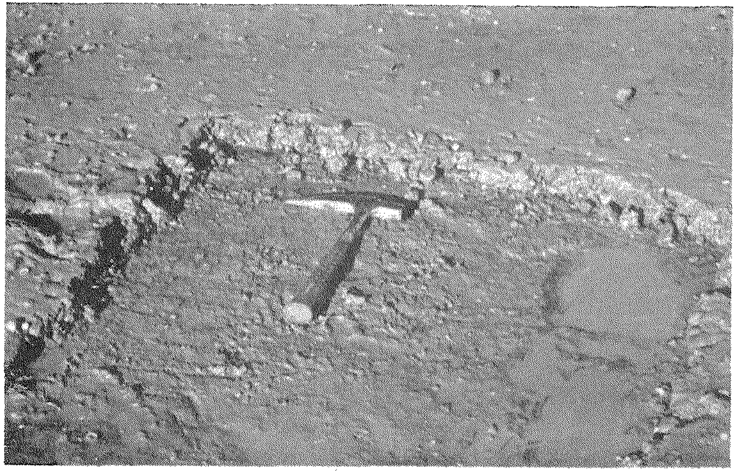


Fig. 6. (*left, above*) A typical meandering runnel, about 40 cm wide, draining the upper reaches of a mud flat at mid-tide in the south upper harbour, Raglan Harbour.

Fig. 7. (*right, above*) Shore platform cut in gently dipping muddy Aotea sandstone in the north upper harbour, Raglan Harbour.

Fig. 8. (*left, below*) Excavation of the soft, sticky mud covering the upper reaches of a tidal flat in the south upper harbour, Raglan Harbour, showing a platform of hard, virtually unweathered Whaingaroa Siltstone just below the surface.

GRAIN SIZE DISTRIBUTION CURVES

The most useful information concerning the relation of sedimentary processes to textural responses has come from a study of the slope and shape characteristics of cumulative frequency grain size distribution curves. Visher (1969) has shown how straight-line segments equate with separate log-normal grain populations in the sediment that may be related to different modes of sediment transport (Fig. 12; Table 2).

Dune, beach, bar, and channel deposits in the lower harbour have very similar grain size characteristics, reflecting both the high degree of sediment mixing through transport between these environments and the textural uniformity of material supplied from the coastal zone. Dune sands (Fig. 12A, a) show a single, very well sorted saltation population indicative of aeolian transportation and deposition. Beach, bar, and channel samples (Fig. 12A, b–d) show two log-normal saltation populations which for beach deposits are related to sorting by swash and backwash action and in channel deposits to variations in the strength of flood and ebb tidal currents. The sands of the west coast undergo considerable sorting during longshore transportation from coastal Taranaki, hence the lack of a traction population in these sediments.

On passing from the lower to middle and upper harbours, and also into the minor arms of the lower harbour, the following changes occur in the grain size distribution curves (Fig. 12B; Table 2).

1. The quantity and sorting of the saltation population decreases, reflecting less reworking because of lower current speeds.
2. A variable, but generally small, amount of poorly sorted traction population material appears in response mainly to shore line erosion.
3. An increasing quantity of suspension material occurs in response to an overall lowering of environmental energy.
4. Highly variable mixing of the different populations indicates that, while low competence currents are typical, energy conditions are more variable or turbulent.

Not all sediments of the upper harbour are indicative of deposition from low-energy currents. Many samples from tidal flats in the north upper harbour and from the lower reaches of channels in the south upper harbour have mean sizes in the medium sand grade and show moderately sorted traction populations comprising up to 50% of the sediment (Fig. 12B, d).

The use of grain size distribution curves for providing information on sedimentary processes may be illustrated by comparing characteristics of samples collected along a transect across the entrance to the north upper harbour (Fig. 13). Here the bottom profile shows a broad, shallow, eastern channel and a narrow, deeper, western channel separated by an intertidally exposed sediment bar. This bifurcated channel is flanked by intertidal flats, wide on the eastern side and narrow on the west. Sediment from the deeper channel (Sample 63) has been transported by relatively low speed, low turbulence currents and deposited almost entirely from suspension and saltation. This may be because the channel was overdeep at the time of sampling, but is consistent with indications from sediments in the north upper harbour that the highest current flows are not always in the channels. Sediment from the intertidal bar (Sample 64) indicates the action of more turbulent currents of slightly greater speed, resulting in less deposition of fines from suspension. The very poorly sorted traction population of sediment from the bottom of the broad shallow channel (Sample 65) is interpreted as a lag deposit. The coarse-end truncation point (-2ϕ) of the traction population indicates the presence of high current speeds. The 2ϕ coarse truncation point of the saltation population (cf. 2.5ϕ in other samples) reflects high shear at the depositional interface caused by high bed-layer velocities, although low turbulence currents are suggested by the insignificant mixing between saltation and traction populations. High current strengths near the margins of the shallow channel have removed or prevented deposition of all but a small quantity of fines (Sample 66). Sediments here have been deposited almost entirely from bed-load material. The $0–2.5\phi$ population may be traction deposited and the coarser than 0ϕ populations lag material. Alternatively, only 10–15% of the sediment may be lag, with the remainder of the bed-load material being sorted into discrete log-normal subpopulations, because of differences in the strength of ebb and flood tidal flows. Sediment from near the eastern shore line (Sample 67) is still dominated by bed-load material, indicating that currents remain strong, although of lower speed than in the channel. Here there is extreme mixing between grain size populations which indicates high turbulence, probably the result of wave action or eddying of tidal currents close to the shore line.

Fig. 13C gives a relative assessment of the current speed and turbulence across the profile based on these considerations.

GRAIN SIZE PARAMETERS

Grain size parameters for muddy samples cannot be calculated without first obtaining the size distribution within the mud fraction by tedious pipette analyses. Such analyses do not warrant the additional information gained as their reliability and significance are dubious (Visher 1969, Nelson 1977). Instead, grain size parameters were calculated for the terrigenous

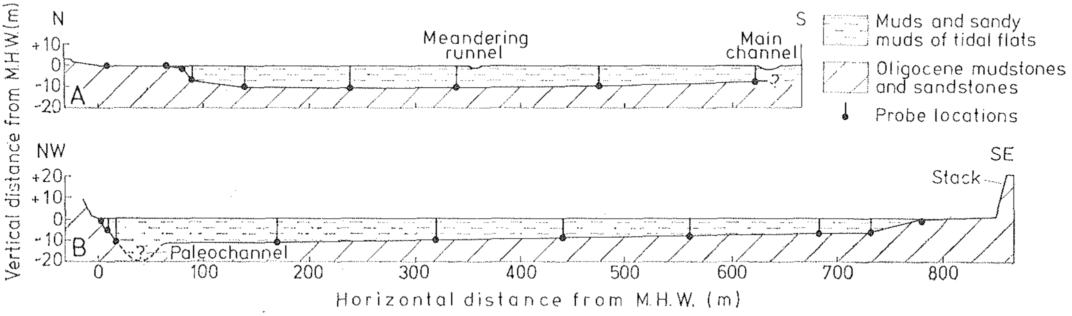


Fig. 9. Profiles of shore or rock platforms extending beneath the tidal flats of Raglan Harbour. Vertical exaggeration 2x. Section lines A & B are shown on Fig. 4. M.H.W. = mean high water.

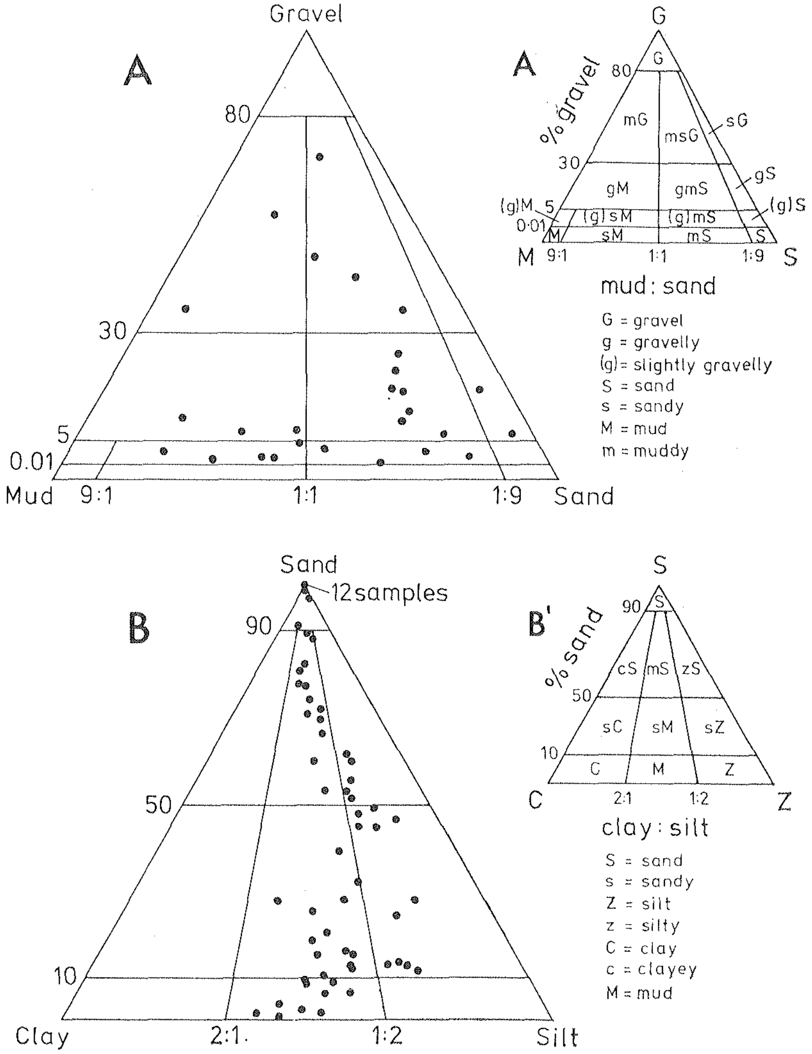


Fig. 10. Triangular textural plots of gravel-bearing (A) and gravel-free (B) sediments from Raglan Harbour. A¹ and B¹ show the textural class names proposed by Folk (1968).

sand and gravel fraction alone. Isopleth maps showing variations in the statistical parameters $Mz\phi$, $\sigma_I\phi$, Sk_I, and K_G throughout the harbour are available on request. Data from these maps reinforce the general conclusions made on the basis of the distributions of major textural groups (Fig. 11) and from the analysis of grain size distribution curves (Fig. 12). The major conclusions from the isopleth maps for grain size parameters are summarised briefly below.

MEAN GRAIN SIZE ($Mz\phi$). The mean size of sand in the lower harbour falls predominantly in the medium sand grade, in the deeper parts of the middle harbour in the fine sand grade, and in the extensive tidal flats of the middle and upper harbours in the very fine sand grade. Concentrations of coarser sands occur in the vicinity of the Narrows (Fig. 4), where the speed of tidal currents is greatly accentuated by the constricted entrance to the south upper harbour, and locally about the margins of the harbour where sediment is derived directly from shore line erosion or incoming streams.

Pipette analyses of a few samples showed that the true mean size of the mud-dominated tidal flat sediments in the middle and upper harbours ranges widely from coarse silt to clay, but commonly falls near the silt-clay (8ϕ) boundary.

SORTING ($\sigma_I\phi$). Sorting values for the sand and gravel fraction are indicative more of maximum rather than mean energy conditions in the depositional environment. Samples from the lower harbour and much of the middle harbour were well or very well sorted, consistent with a combination of strong current action and the supply of well sorted material. Marginal sediments of the middle harbour, together with those of the seaward part of the south upper harbour and the more distal regions of the north upper harbour, are mainly poorly sorted, indicating that the supply of detritus in these areas is greater than the sorting capacity of the currents.

Sediments from the distal parts of the south upper harbour and the central regions of the north upper harbour are moderately to very well sorted. This suggests that the supply of detritus, which may be initially sorted to some degree, is low compared with the sorting efficiency of the currents in these generally very shallow parts of the harbour. If this is so, then it appears that part of the sediment supply to the south upper harbour is transported from the middle harbour via the Narrows by the flood tide.

SKEWNESS (Sk_I). Near-symmetrical skewness is confined to well-sorted sand in the main channel of the lower harbour. Dune, beach, and some bar sands are fine-skewed, probably because of the concentration of titanomagnetite in the very fine sand fraction. The majority of the sand and gravel fraction in the remainder of the harbour is coarse- or strongly coarse-skewed which indicates an excess of coarse grain sizes, perhaps mainly as lag material. This is consistent with removal or non-deposition of fines during periods of highest current activity.

KURTOSIS (K_G). No readily interpretable pattern emerges from the distribution of kurtosis values in Raglan Harbour sediments; values ranged from platykurtic to very leptokurtic. We agree with Baker (1968) that the use of graphic kurtosis as a descriptive parameter should perhaps be abandoned.

SEDIMENT TRANSPORT AND DEPOSITION

The small ratio of the total volume of water in Raglan Harbour to the spring tidal compartment (Table 1) shows that flows in the harbour are completely dominated by tidal currents (Heath 1976). Surface speeds of 75–150 $cm.s^{-1}$ and 50–100 $cm.s^{-1}$ are typical in the lower and middle harbour arms respectively (Admiralty Chart N.Z. 4421 1962). Deposition of sediments is controlled by complex variations in the speed and direction of ebb and flood tidal flows. Current measurements at a station in the lower harbour (Fig. 4) showed higher speeds for shorter periods during the flood tide than for the

Table 2. General characteristics of grain size distribution curves for major sediment types from the lower, middle, and upper reaches of Raglan Harbour. C.T. & F.T., coarse and fine truncation points respectively (see inset, Fig. 12); A, B, and C, saltation, suspension, and traction populations respectively; –, not applicable.

	Saltation population (A)				Suspension population (B)			Traction population (C)		
Reach	(%)	Sorting ($\sigma_I\phi$)	C.T. (ϕ)	F.T. (ϕ)	(%)	Sorting ($\sigma_I\phi$)	Mixing A & B	(%)	Sorting ($\sigma_I\phi$)	Mixing A & B
Lower Harbour	100	Well to very well	–	–		–	–		–	–
Middle Harbour	35–75	Moderate to mod. well	1.7–3.0	3.5	<20	Poor	Much	1–55	Poor	Much
Upper Harbour	30–60	Moderate	2.7	3.7	40–50	Poor	Little	2–20	Poor	Little

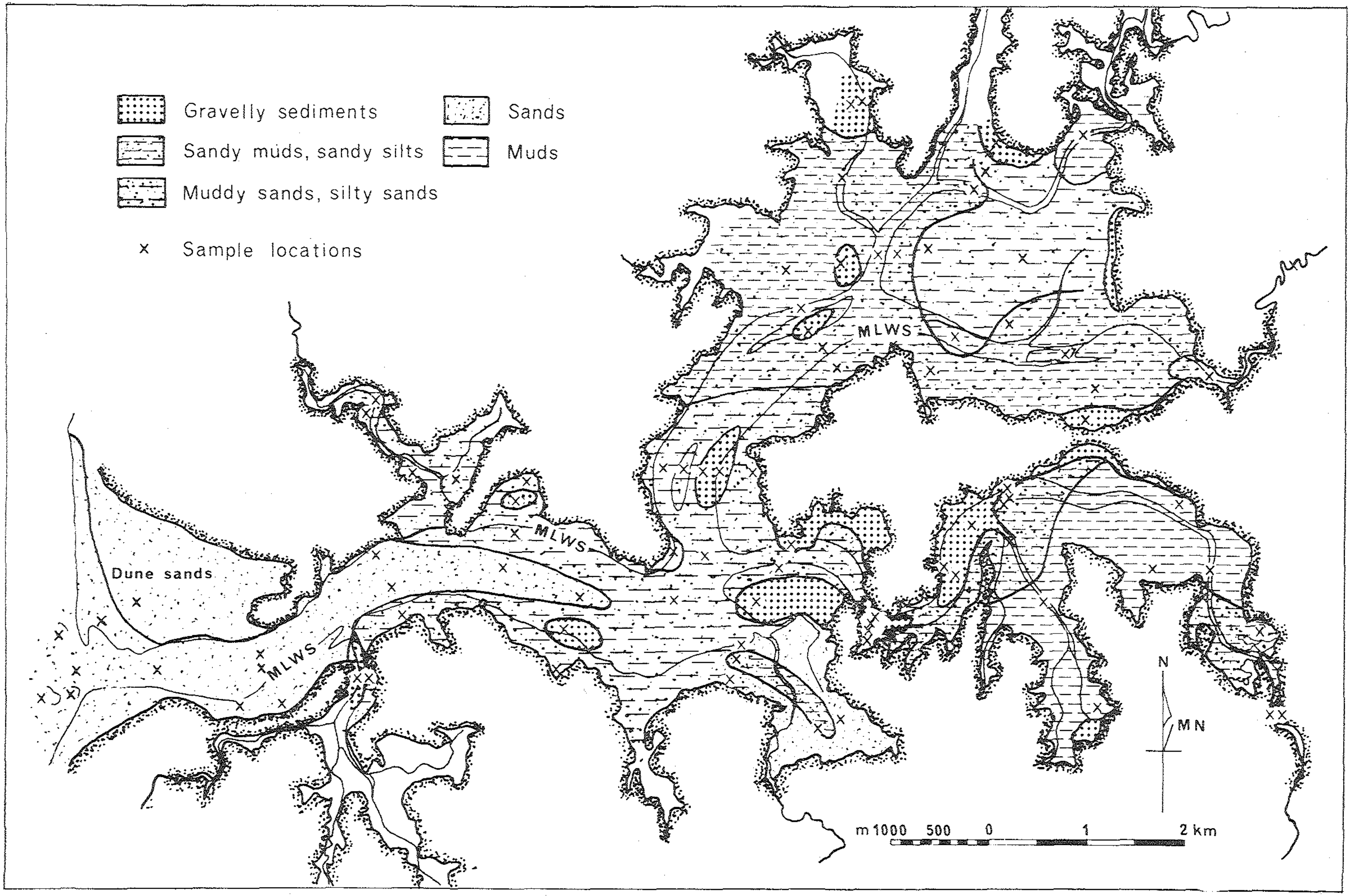


Fig. 11. Distribution of major textural groups of sediments in Raglan Harbour (MLWS, mean low water spring)

ebb tide (Fig. 14). The relationship between ebb and flood currents in other parts of the harbour can only be inferred.

Suspended sediment concentrations at the same station varied between 10 and 100 mg.L^{-1} and indicate net seaward displacement of fines (Fig. 14). High current speeds throughout the tidal cycle prevent any net deposition of suspended material in the channel of the lower harbour.

In general, the quantity of bed-load material decreases up-harbour as a function of decreasing current speed, although bed-load populations make up 2–50% of tidal flat sediments. Deposition of sediments consisting mainly of bed-load material is readily explained in terms of depositional and critical erosion velocities (Allen 1970). Small quantities of suspended material may be incorporated in sandy sediments if deposition is sufficiently rapid. However, the deposition and preservation of muddy sediments in tidal areas is less simple.

In estuaries and tidal inlets deposition of suspended material is largely restricted to periods of low current flow and slight turbulence occurring at slack water. Sedimentation of mud from suspension is appreciable only if current speeds drop below about 20 cm.s^{-1} (Einstein & Krone 1962). In Dutch tidal waters these conditions occur for an average period of about 2 h at each turn of the tide, when up to 0.3 cm of unconsolidated mud may be deposited (Terwindt & Breusers 1972).

Why is a layer of mud, deposited during a period of slack water, preserved and not resuspended when current speed and turbulence increase with the turn of tide? Furthermore, how is sand, transported as bed load, incorporated into sediments consisting largely of suspension-deposited material without erosion of the latter? Several factors appear to be relevant: (1) critical erosion velocities for silt and clay are frequently much higher than those for sands due to cohesive as well as frictional forces opposing water flow (Sundborg 1956); (2) Terwindt & Breusers (1972) have shown that consolidation of mud in the first few hours after deposition increases the critical shear velocity for initiation of sediment movement, and that a sand content of up to 40% gives a more rapid initial consolidation. Muds in Raglan

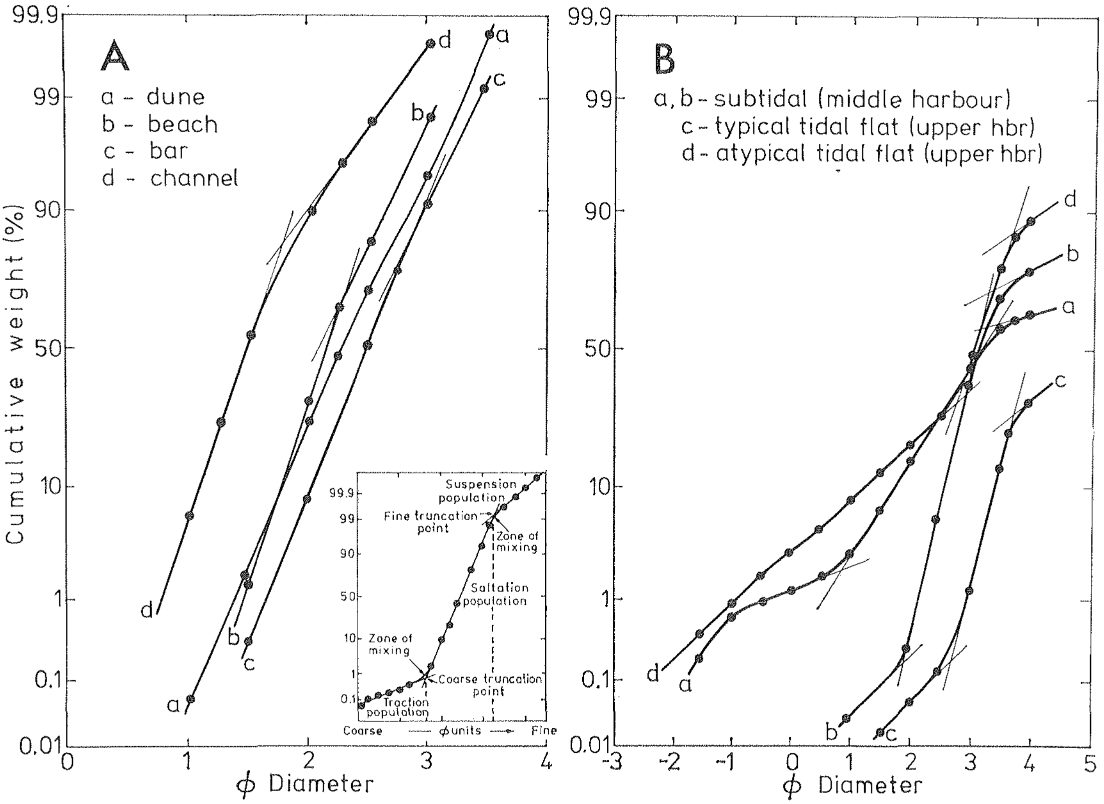


Fig. 12. Grain size distribution curves typical of sediments from various environments in Raglan Harbour. Inset shows the terminology of Visher (1969) for log-normal segments of a cumulative frequency curve plotted on probability paper.

Harbour are typically sandy (Fig. 10B) and as a large proportion of these muddy sediments is deposited on tidal flats it is likely that most of the initial consolidation process occurs subaerially; (3) mud may be deposited from tidal currents of fairly high velocity where the concentration of suspended sediment exceeds about 100 mg.L^{-1} (McCave 1971); (4) mud may accumulate as sand-sized floccules or fragments and as sand-sized faecal pellets; and (5) fine sand may be transported in sand-clay floccules (Biddle & Miles 1972), which could result in wrong conclusions about sediment transport deduced from textural analyses. In addition, we have observed small grains of sand being transported by flotation in Raglan Harbour (cf. Wolf 1961), but the long-term significance of this mechanism is unknown.

The distal estuarine regions of Raglan Harbour form a distinct environment. During flooding, streams dump very poorly sorted gravels at their points of entry into the harbour as a result of their sudden loss of competence. Flocculation of clays entering the harbour, especially of 2:1 lattice clays such as montmorillonite, probably occurs in these estuarine reaches. Moreover, low turbulence and current speeds allow deposition from suspension to occur over most of a tidal cycle, forming sediments with up to 98% mud. Elsewhere in the harbour, sediments are generally coarser because turbulence is low enough to

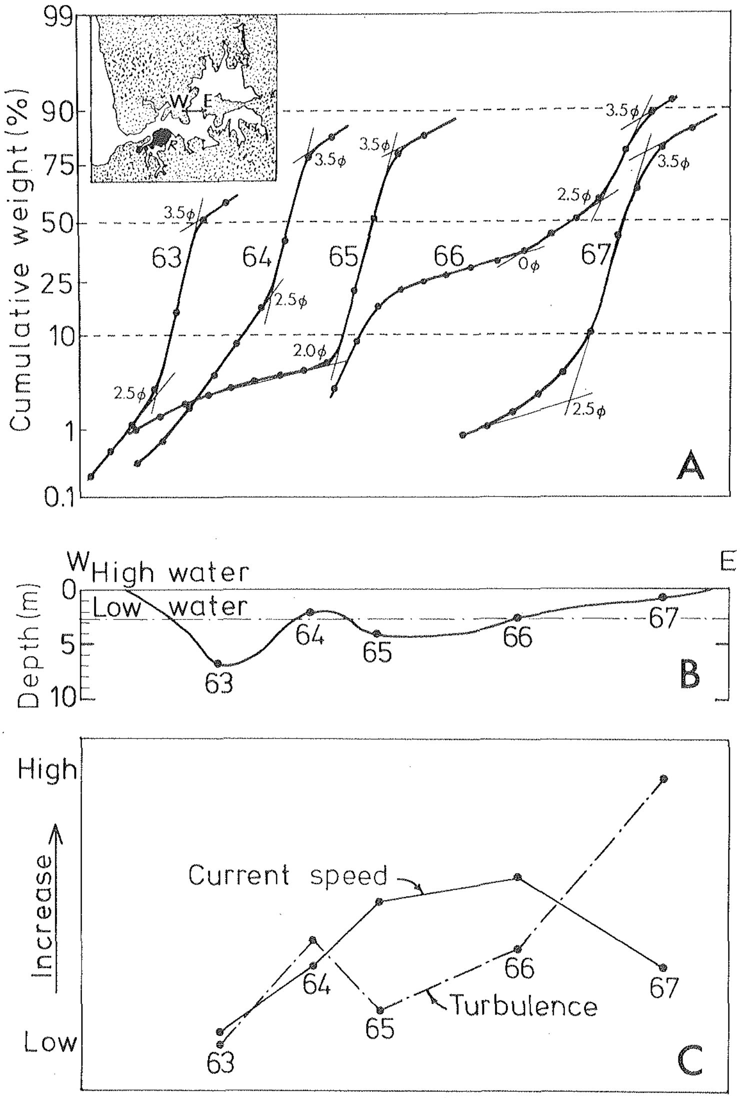


Fig. 13. Relative importance of current speed and turbulence (C) in controlling the texture of sediment samples collected from a transect across the arm joining the middle and north upper harbours (B), Raglan Harbour, assessed from characteristics of the grain size distribution surves for the sediments (A).

allow deposition from suspension for only a short period during a tidal cycle.

The finest-grained sediments in the north upper harbour occur in the channels, and grain size distribution curves show that sediment on the adjacent tidal flats is transported as bed-load. This suggests that maximum current speeds are attained at stages of the tidal cycle when the flats are covered with water and the currents are not confined to the channels. At low water, when water is confined to the channels, currents are weak and allow deposition from suspension. This apparently anomalous textural pattern, however, may be a reflection of greater wind-wave winnowing on the flats in the large north upper harbour or, perhaps, that these sediments are not yet in equilibrium with present hydraulic conditions. The equilibrium problem is complex and a detailed survey of current velocities is needed to show conclusively whether or not the textural distribution is primarily a function of current strength.

COMPOSITION

BULK SEDIMENT MINERALOGY

The bulk mineralogy of Raglan Harbour sediments (Fig. 15) consists of quartz, plagioclase and potash feldspars, clay minerals, calcite, aragonite, titanomagnetite, and ferromagnesian minerals. Samples (7 & 15) taken from near the mouth of the harbour differ markedly from those taken from other localities. Their mineralogy is dominated by titanomagnetite and ferromagnesian minerals, and clay minerals are lacking, and closely resembles the composition of the coastal ironsands (Gow 1967). Up-harbour the amount of quartz, plagioclase feldspar, and clay minerals increases considerably as heavy minerals become a less important component of the sediments. Calcite and potash feldspar remain minor constituents. A comparison of this bulk mineralogy with that of Mesozoic and Tertiary sediments about the harbour (Nelson 1973) strongly suggests that these rocks are the major source of terrigenous material in the harbour (Fig. 16). However, the dominance of heavy minerals near the mouth of the harbour, and their appearance in all sediments examined, shows that another provenance is important.

CLAY MINERALOGY

The mineralogy of the less than 2 μm fraction consists mainly of illite and montmorillonite, with common mixed-layer illite-montmorillonite and chlorite, and some kaolinite and halloysite (Fig. 16C), with only minor amounts of quartz, feldspar, and calcite. The broad and rather diffuse nature of most basal reflections for clay minerals on X-ray diffractograms shows that they generally have poor crystallinity.

The bulk of the clay mineral assemblage can be explained by derivation from either the adjacent Mesozoic and Tertiary sediments (Fig. 16D) or from the soils developed on them. The regolith of the Mesozoic sandstones and mudstones is locally very thick (up to 30 m), and often deeply red weathered. Soils in these sections are dominated by kaolinite, illite, and interlayered hydrous micas derived from the alteration of chlorite and micas in the parent rocks (Nelson 1973, Hume 1978). The small amounts of halloysite are derived from the local Quaternary ash cover.

HEAVY MINERALOGY

The heavy mineralogy is dominated by titanomagnetite and diopsidic augite with less abundant hornblende and hypersthene. Epidote, biotite, leucoxene, and uncommon accessory heavy minerals are important only in the more distal reaches of the harbour. Up-harbour percentages of total heavy minerals and individual minerals in the fine sand fraction are summarised in Fig. 17.

Titanomagnetite. Blue-black in reflected light and strongly magnetic. The larger grains are commonly subrounded, tending to euhedral shapes with decreasing grain size. Grains commonly show evidence of solution pitting, often in the form of hexagonal-shaped cavities, which may be related to exosolution of the rhombohedral phase, as discussed by Wright (1964). Titanomagnetite also occurs as inclusions in augite, and, less commonly, in hornblende, hypersthene, and epidote.

Leucoxene and haematite. Leucoxene exists as an alteration product of ilmenite and is recognised by its dusty grey appearance in reflected light. Haematite occurs mainly as coatings on opaque grains, including foraminifers and other biofragments (e.g., echinoderm and bryozoan grains).

Augite. Diopsidic augite has variable appearance and may be confused with both epidote and hypersthene. Augite occurs mainly as subrounded subhedral grains, but ranges from well rounded grains to angular euhedral prisms. Pale bottle green is the most common colour with yellowish green pleochroism in many grains, although thin cleavage flakes are almost transparent. Many grains show solution embayments on (100) faces and some show ragged (001) faces, indicative of solutional alteration. Some grains are reduced to a remnant rim of augite surrounding an opaque inclusion. Inclusions are common and are mainly titanomagnetite and apatite.

Hornblende. Characterised by very strong pleochroism and a very deep body colour which frequently causes the grains to appear opaque. Grains are usually elongate with well developed cleavage and some show ragged (001) terminations indicative of solutional alteration. Two varieties are distinguished on the basis of pleochroism, namely yellowish green or green to very dark green, and reddish brown to deep red-brown. The first is the most abundant and commonly shows opaque inclusions.

Hypersthene. Generally occurs as subangular prisms with a squarish outline, but subrounded to rounded prisms, sometimes elongate, are also common. Some grains exhibit ragged (001) terminations. Colour is light green or greyish green to pinkish green or pinkish brown and most grains are pleochroic in these tints. Inclusions of opaque minerals, gas bubbles, and apatite occur, but are generally not as abundant as in augite.

Epidote. Subrounded to well rounded grains and subhedral plates, often exhibiting extensive solutional alteration, are the most common forms. Most grains contain some inclusions of opaque minerals and apatite. Colour varies from light bottle green to yellowish green or greenish brown, often with pleochroism in these tints.

Biotite. Irregularly shaped, brown or green cleavage plates of biotite occurred in minor amounts in about half the samples examined.

Zircon. Most heavy mineral concentrates contained a few worn prismatic grains of colourless to very pale pink zircon.

Apatite. Colourless, generally equidimensional, subrounded grains of apatite, often with iron-stained margins and fractures, occurred in minor amounts in most samples.

Sphene. A few worn grains of sphene showing incomplete extinction and very high order gold-blue-grey interference colours were identified.

Garnet. Rare, worn, and fractured grains of pale pink almandine garnet were present in a few samples.

Tourmaline. Very rare prismatic grains of strongly pleochroic tourmaline occurred in some samples.

Sources for the heavy minerals in Raglan Harbour include the hinterland Mesozoic and Tertiary sedimentary rocks (mainly ilmenite, leucoxene, biotite, hornblende, augite, epidote, zircon, and apatite (Nelson 1973)), the Alexandra Volcanics (mainly augite, hornblende, and opaques (Henderson & Grange 1926)), the Quaternary tephra deposits (mainly augite, hornblende, hypersthene, and magnetite (Hogg 1974, Salter 1979)), and the coastal ironsand deposits (mainly titanomagnetite, diopsidic augite, hypersthene, green-brown hornblende, and red-brown hornblende (Gow 1967)). The relative importance of coastal and hinterland provenances can be assessed from the relative abundance of these heavy minerals. In the lower and middle harbour, titanomagnetite is concentrated in the deepest parts as a result of washing out of lighter minerals by strong currents (Fig. 17). The high percentage of titanomagnetite in the small northern arm of the lower harbour (Sample 21) is the result of deposition of sand blown from the nearby coastal dunes by the prevailing south-westerly winds, rather than by hydraulic action, as shown by the abundance of frosted quartz grains in the light mineral fraction. From the coast through the middle harbour into the south upper harbour (Samples 7, 15, 26, 44, 59, & 61) the titanomagnetite

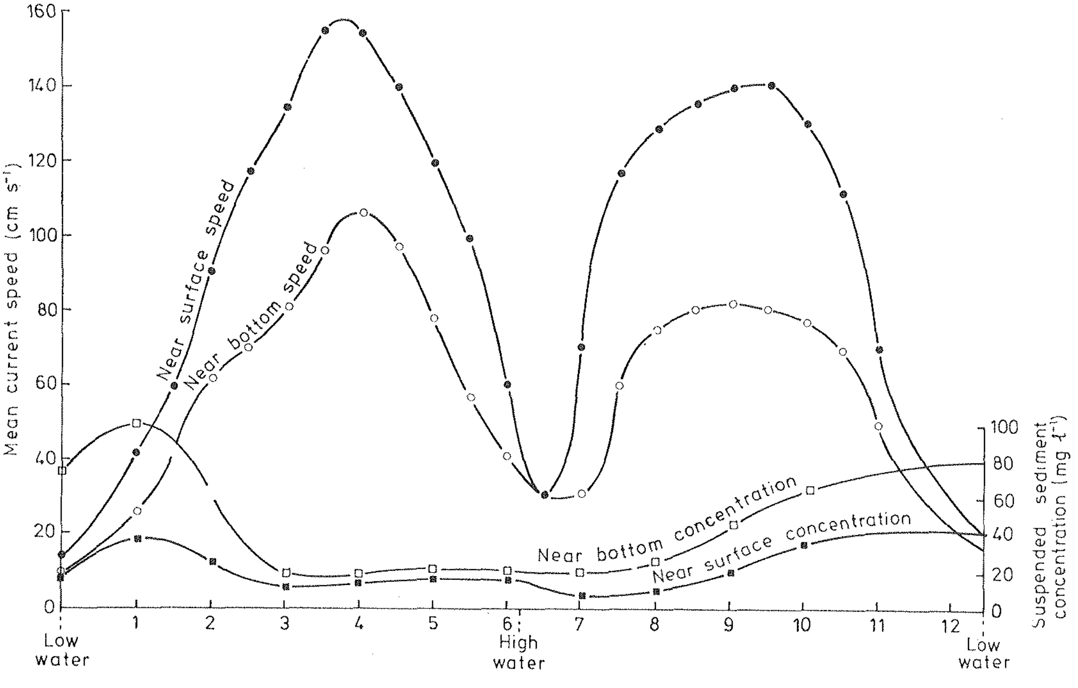


Fig. 14. Tidal current speeds (circles) and suspended sediment concentrations (squares) over a spring tidal cycle at station H (Fig. 4) in the lower harbour, Raglan Harbour.

content decreases steadily (from 75 to 25%) as the epidote content increases (0 to 13%). The augite concentration remains more or less constant (25 ± 5%) and the difference between the trends of titanomagnetite and augite, both from the same provenance, is interpreted as due to a difference in their specific gravities causing selective sorting and transport of the lighter mineral further up the harbour on the waning flood tide. From the lower to the north upper harbour (Samples 7, 15, 26, 65, 70, 93, & 91), titanomagnetite concentrations show first a decrease from the coast to the middle harbour and then an increase towards the north-east end of the upper harbour. Significantly the latter portion has the longest fetch (7 km) in Raglan Harbour, in the direction of the prevailing south-westerly wind. Thus the reversal in the general trend of decreasing titanomagnetite concentration in this section of the harbour is attributed to piling up by wave action. Titanomagnetite concentration increases with decreasing depth and increasing wave action up the north upper harbour, culminating in extremely high concentrations (>95%) on small beaches facing the southwest (e.g., Sample 91).

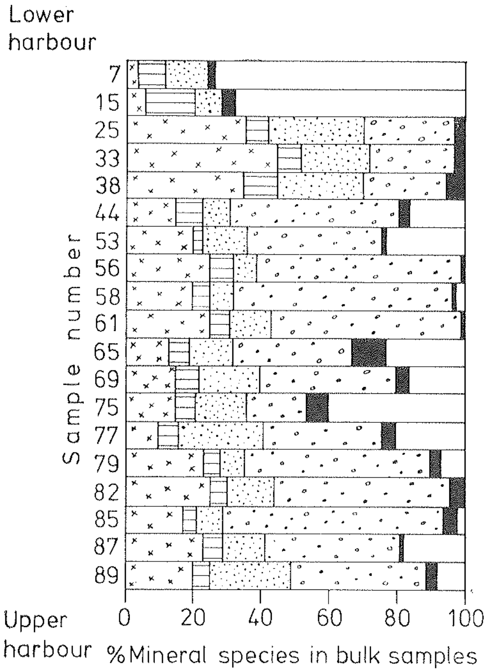


Fig. 15. Bulk mineralogy of Raglan Harbour sediments presented in the form of a rough transect from the mouth to the distal reaches of the harbour. Others = mainly titanomagnetite, ferromagnesian minerals, and/or aragonite.

Zircon, leucoxene, limonite, and apatite, derived from Tertiary and Mesozoic rocks, are conspicuously more common in samples from distal regions of the harbour. No quantitative assessment has been attempted, however, as their concentrations are usually less than a dozen grains per sample.

LIGHT MINERALOGY

The light mineral fraction consists of quartz, feldspar, glass shards, and rock fragments. No quantitative estimations were made, but some morphological characteristics of grains are noted below.

Quartz. Several varieties of quartz are distinguished:

1. Angular to subrounded, anhedral to subhedral, watery clear quartz is the dominant quartz variety in harbour sediments.
2. Subangular to rounded, clouded quartz grains were relatively common in samples.
3. Rounded to well-rounded grains with strongly pitted surface textures were most common near the harbour entrance.
4. Euhedral, watery clear, hexagonal bipyramidal crystals of volcanic heritage occurred in some samples.
5. Subangular to subrounded multicrystalline quartz grains occurred in small quantities in most samples.
6. Rare grains of mainly anhedral, highly vacuolated quartz.
7. Chalcedony and chert fragments were present in some samples.

Varieties 1, 2, 5, and 7 are derived mainly from Mesozoic and Lower Tertiary sedimentary rocks, variety 3 from coastal sand dunes, variety 4 from local Quaternary tephra beds, and variety 6 from quartz veins in the Mesozoic basement rocks.

Feldspar. Subhedral grains of feldspar, dominantly plagioclase, are common in most samples, and range from occasional fresh, watery clear cleavage flakes to more abundant worn, heavily kaolinitised and sericitised grains. Some grains were zoned and a few showed gridiron (or microcline) twinning. Most feldspar is derived from the Mesozoic and Tertiary sediments, some from the hinterland volcanic rocks.

Glass shards. Watery, clear glass shards with conchoidal fractures and gas-filled vacuoles were common in some samples, being derived from the Quaternary ash mantle.

Rock fragments. These were abundant in some samples and are polygenetic. Examination of the gravel-sized rock fragments during grain size analysis showed that pellets of Whaingaroa Siltstone were the most common rock fragments. Mesozoic "greywacke" fragments were common in some samples, while fragments of Aotea Sandstone, Waitetuna Limestone, Alexandra andesites, and reworked rock fragments from Mesoic rocks were of local and generally minor importance.

The nature of light minerals reflects a multiple source, dominated by grains from Tertiary and Mesozoic sedimentary rocks, but also from Quaternary tephras and from wind and water transported coastal sand.

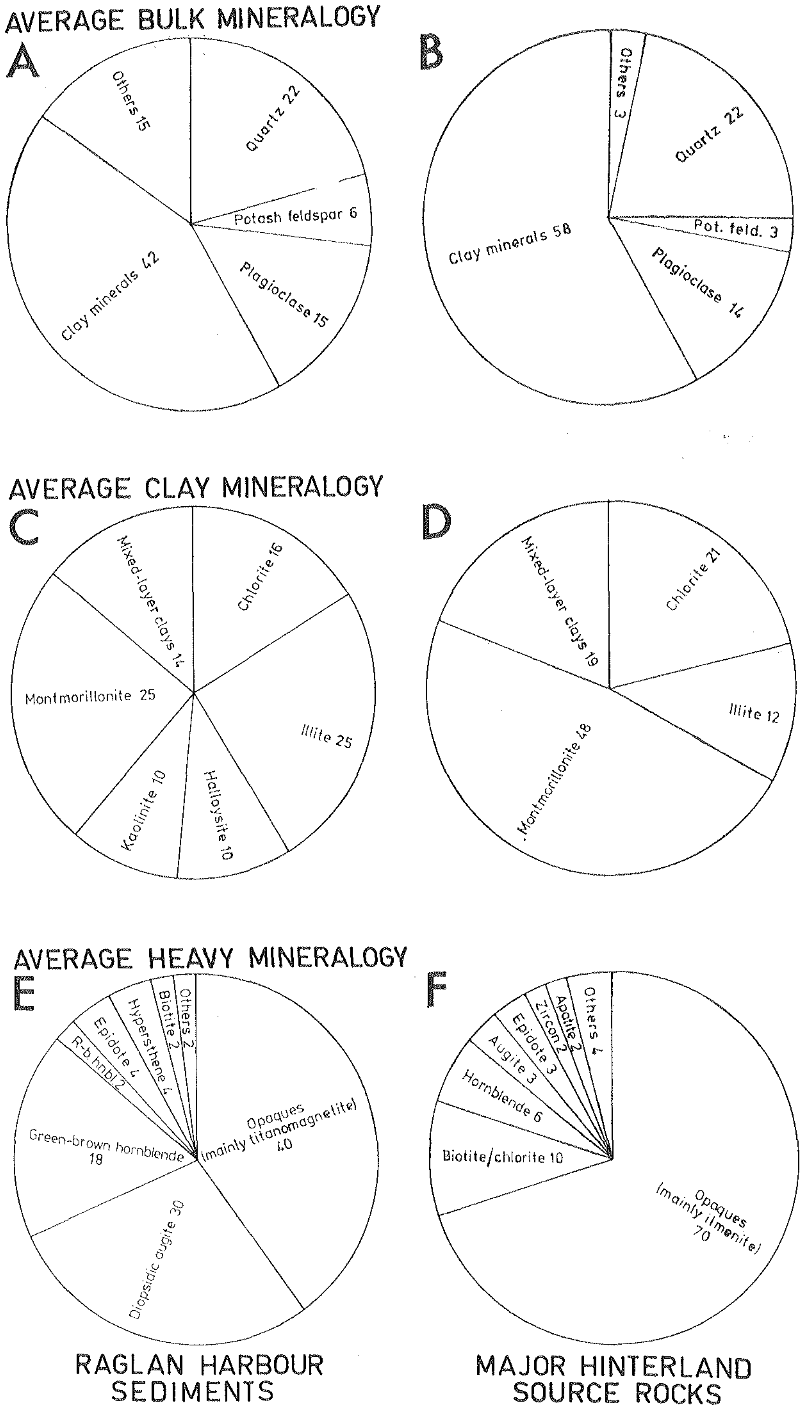


Fig. 16. Pie diagrams comparing the average bulk (A), clay (C), and heavy (E) mineralogy of Raglan Harbour sediments with the average bulk (B), clay (D), and heavy (F) mineralogy of the Mesozoic and Oligocene sedimentary rocks in the Raglan Harbour drainage basin. Average bulk mineralogy calculated on a calcite-free basis. Data for B, D, and F are mainly from Nelson (1973).

CARBONATE CONTENT

The calcium carbonate content of 94 harbour samples averaged about 12% by weight and ranged from practically 0 to almost 100% by weight. It is mainly aragonite supplied by the intrabasinal, predominantly molluscan, benthos. The small quantities of calcite are derived from erosion of calcareous rocks of the Te Kuiti Group. Carbonate-rich sediments tend to be concentrated in regions of strong currents. An isopleth map is available on request.

ORGANIC MATTER

Organic matter in sediments increases up-harbour, apparently reflecting the fining of sediments in the same direction. Approximate values (% by weight) are 0 for the lower harbour, 1 for the middle harbour, 2 for most of the upper harbour, and 3 for the distal reaches of the north and south upper harbours. The main source is probably the decay of soft tissues of benthic organisms, especially molluscs, together with faecal material, zooplankton, phytoplankton, and shallow-water rooted vegetation. An isopleth map is available on request.

Fine sediments of tidal flats usually contain over 10% by weight organic matter (Kukal 1971). The low organic matter content of Raglan Harbour sediments may result from a supply of organic matter only slightly in excess of the supply of oxygen to the sediment-water interface, or may indicate hyperactivity of sulphate-reducing bacteria in the reducing layer immediately below the surface, as is suggested by the strong odour of hydrogen sulphide.

Most of the harbour sediments have an upper oxidising layer, usually 1–2 cm thick, on a reducing layer of undetermined thickness. This layering is most clearly defined in fine-grained sediments of the tidal

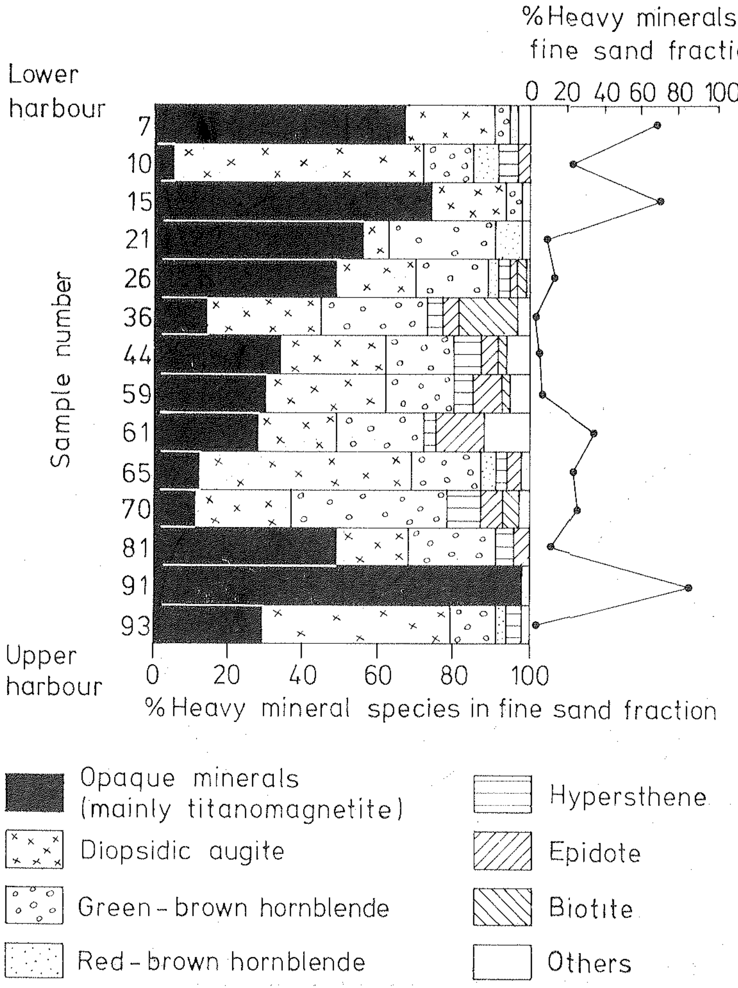


Fig. 17. Heavy mineralogy of the fine sand fraction of Raglan Harbour sediments presented in the form of a rough up-harbour transect.

flats. The oxidising layer is brown to light reddish brown due to ferric iron. A 'soupy' texture is characteristic because of the extremely high water content. The reducing layer is olive grey to black due to metacolloidal hydrotroillite, a black, fine-grained iron sulphide (Berner 1971). Expulsion of water during initial consolidation makes it firmer than the oxidising layer, but it nevertheless remains extremely plastic.

PHOSPHATIC CONCRETIONS

Diagenetically, the occurrence of Subrecent to Recent phosphatic concretions is of interest (Fig. 18). The concretions lie on, or are partially embedded in, the soft mud of the tidal flats, amongst living and dead molluscs. Their shape ranges from small spheres, a few centimetres in diameter, to multi-lobed masses up to 55 cm across. They enclose a fauna, mainly *Chione, Cyclomactra,* and *Zeacumantus,* all members of the modern benthos.

The largest expanse of concretions occurs in the south upper harbour adjacent to an old shore platform which stands 30 to 40 cm above the modern tidal flats and consists of little more than a mass of sediment-filled vertical borings, weakly cemented together. The platform is possibly relict from a +0.5 m Holocene stand of sea level recorded elsewhere in the harbour by Wellman (1962; p. 65). Peripheral erosion of this platform to tidal flat level has exposed the litter of concretions which are now encrusted with barnacles and other marine growths and are not forming at present. Concretions also occur directly beneath the old platform and appear to be actively forming. They have gradational contacts with the soft surrounding mud and preserve partly embedded bivalve shells with soft mud infillings. It is possible that the high alkalinity required for phosphate precipitation (Berner 1971) has been provided by the decay of the boring organisms in the shore platform.

Semiquantitative X-ray diffraction and chemical analyses show that the concretionary material consists mainly of disordered apatite (50%), clay minerals (30%) of similar composition to those in the modern tidal flats, calcite and skeletal aragonite (15%), and quartz (5%). Thin sections show grains of quartz and opaque minerals in a nondescript cryptocrystalline groundmass.

CONCLUSIONS

The texture and mineralogy of surficial sediments in Raglan Harbour reflect complex interactions between supply of sediment from a number of provenances and the tidal circulation system controlling sediment transport and deposition.

1. Sediment composition and derivation. The bulk sediments consist of quartz, potash and plagioclase feldspars, the clay minerals illite, montmorillonite, mixed-layer illite-montmorillonite, chlorite, kaolinite, and halloysite, the carbonates calcite and aragonite, and the heavy minerals titanomagnetite, diopsidic augite, hornblende, hypersthene, epidote, biotite, and leucoxene. Near the harbour entrance they are dominated by tianomagnetite and ferromagnesian minerals

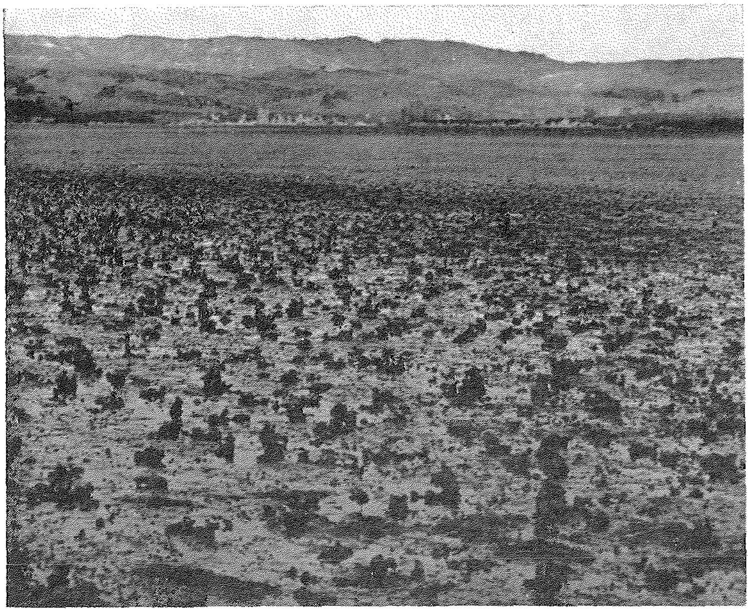


Fig. 18. Irregularly shaped phosphatic concretions, averaging about 10 cm across, littering large area of intertidal mud flat in south upper harbour, Raglan Harbour.

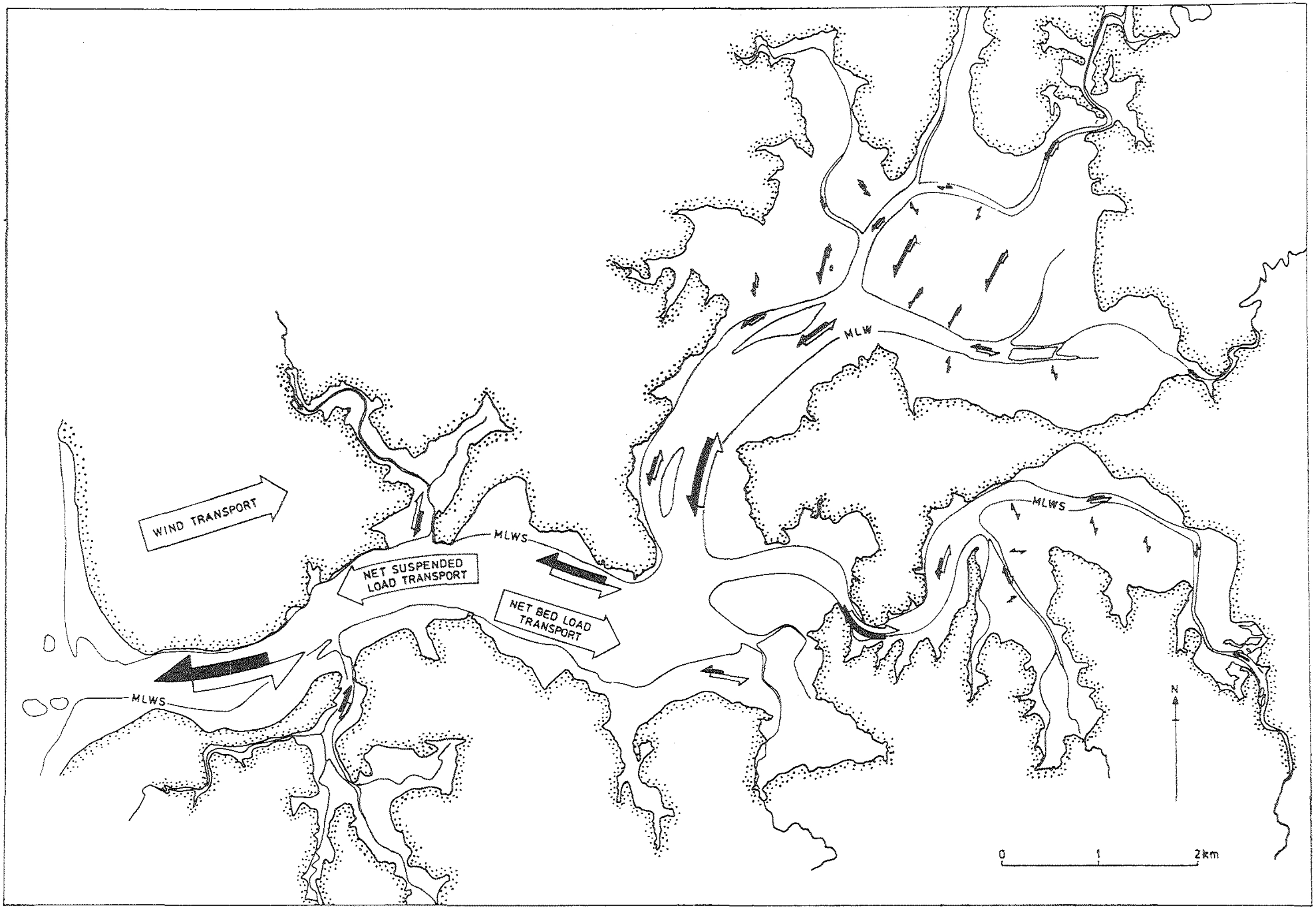


Fig. 19. Relative velocities of ebb and flood tidal currents in Raglan Harbour, inferred from the interpretation of mineralogical and textural data, and directions of net sediment movement. Size of arrows proportional to current speed.

derived from the coastal ironsands. Elsewhere, sediments consist mainly of quartz, plagioclase feldspar, and clay minerals derived from the hinterland, although a coastal ironsand provenance is the source of part of the sand fraction even in the most distal reaches of the harbour. Benthic organisms, mainly molluscs, supply most of the carbonate material and organic matter in sediments, besides being agents of considerable sediment reworking.

2. *Sediment transport and deposition.* Energy conditions vary from the highly turbulent sand-bar and ocean beach environments near the harbour entrance to tranquil estuarine conditions in the distal reaches of the harbour. Sands in the lower harbour are progressively replaced up-harbour by more muddy sediments. Gravelly sediments occur sporadically throughout and are generally products of shore line erosion or are lag deposits in channels. The fastest currents, reaching 160 cm.s^{-1} in the lower harbour, are usually confined to the main channels. However, in the north upper harbour, and to a lesser extent in the lower reaches of the south upper harbour, the finest-grained sediments occur in the channels. It appears that in these areas maximum current speeds are reached at those stages of the tide when water covers the tidal flats and sand is transported as bed load, although winnowing by wave action may also be important.

The poor sorting and high degree of mixing of log-normal grain size populations in sediments show that deposition occurs under highly variable energy conditions. Bed-load is deposited as tidal flows decrease in velocity, with sedimentation of fines from suspension mainly at periods of slack water. The muds are not necessarily resuspended when current velocities and turbulence increase with the turn of the tide, mainly because of their cohesive nature and their rapid initial consolidation characteristics.

While measurements inside the harbour entrance show a net seaward displacement of suspended sediment (Fig. 14), trends displayed by heavy mineral concentrations (Fig. 17) indicate a net up-harbour transport, undoubtedly with westerly storms contributing to the flood tidal effects.

No attempt is made here to deduce a sediment budget and equate this with the volume of material eroded from the harbour margins; basic data are too sparse. However, mineralogical and textural data are interpreted to infer relative velocities of ebb and flood tides throughout the harbour (Fig. 19), which although indicating prevailing directions of sediment transport, cannot be used to determine net sediment movement; the latter is indicated separately.

3. *Harbour formation.* A large proportion of the tidal flats in Raglan Harbour are sediment-veneered rock platforms showing that the present extent of the harbour does not represent simply the drowned and sediment-infilled relief of a former river valley system. The platforms occur at two distinct levels (Fig. 9). The higher one extends offshore for distances up to about 100 m and has almost certainly been cut during the period of relatively stable sea level (±2 m) over the last 5000 years (Schofield 1962, 1975). Erosion rates indicated for this period of up to 2 cm.y^{-1} (cf. Gill 1973) are reasonable considering the montmorillonite-rich nature of the shore line rocks and their susceptibility to erosion by wetting and drying. The lower rock platform at about −10 m below mean high sea level is far more extensive, occupying large areas of the upper harbour. If cutting rates were similar to those suggested for the modern shore platform then it is necessary to invoke a stable sea level for a period of about 25 000 years. On this basis, and considering the elevation of the platform, it is possible that the lower platform was cut during the interstadial high sea-level stand from 85 000 to 60 000 years ago (Chappell 1974).

The development of extensive, cut platforms in the harbour has produced large quantities of very fine sand, silt, and clay, the latter mainly montmorillonite. Shelf sediments off and to the north of Raglan Harbour are completely dominated by suspension-load material (McDougall & Brodie 1967) with a very high montmorillonite content (Hume 1978), which is consistent with derivation of sediment from Raglan Harbour. However, although the cutting and subsequent dissection of shore platforms during the Pleistocene supplied large quantities of sediment to the shelf, it appears that since the start of drowning by the post-glacial rise of sea level about 8000 years ago (Schofield 1962), Raglan Harbour has acted more as a sediment trap.

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