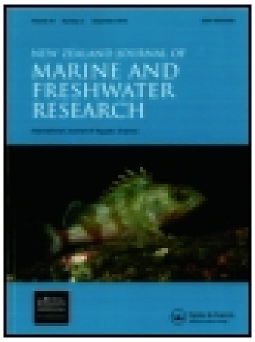

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Sedimentology and evolution of Ohiwa Harbour, a barrier-impounded estuarine lagoon in Bay of Plenty

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Abstract Ohiwa Harbour is a 24 km^2 estuarine lagoon impounded by the 6 km long Ohope spit in the west and the 0.7 km long Ohiwa spit in the east. These barrier sand spits are presently separated by a c. 340 m-wide inlet channel where the maximum harbour depth of 14 m occurs. Seventy percent of the harbour consists of tidal flats supporting a rich shelly benthos and diversified by stands of mangrove and backed locally by salt marsh. Lower harbour sediments in barrier beach, dune, and entrance shoal and channel environments are well sorted, negatively-skewed, medium to fine sands. In contrast, upper harbour sediments are poorly to very poorly sorted, positively-skewed, medium to very fine (silty) sands, the coarser of these deposits occurring in channel and restricted harbour beach environments, and the finer in intertidal flat, creek, and channel bank areas. The terrigenous mineralogy is consistent with a dominantly acid volcanic provenance, directly from the tephra mantle of the catchment and, most importantly, indirectly from the oceanic littoral zone. Sediment dispersal is dominated by tidal currents. Speeds decrease systematically up-harbour from maximum values of 100–150 cm s^{-1} at the inlet channel to 5–10 cm s^{-1} in upper-harbour reaches. Current ripples, megaripples, and sand waves characterise the higher energy, current-dominated lower harbour deposits, whereas small-scale current and wave ripples, together with biogenic markings and burrows, characterise the lower energy, inner harbour deposits. Small amplitude, wind-forced waves are important for resuspending and moving sediment in intertidal areas, particularly on the upper tidal flats. Most areas of the harbour are affected by biological processes. Rapid growth of Ohope barrier spit resulted from increased eastwards transport of littoral sands around Whakatane Heads, west of Ohiwa Harbour. The probable cause of this was the infilling of the up-drift Rangitaiki Plains embayment which was essentially completed soon after the time of the Taupo Pumice eruption (AD 131). Over the last 2000 years Ohope spit has accreted laterally eastwards at an average rate of about 3 m y^{-1}, Ohiwa spit has concomitantly eroded, and there has been accelerated infilling of Ohiwa Harbour.

Keywords Ohiwa Harbour; Bay of Plenty; Ohope spit; Ohiwa spit; estuarine lagoon; tidal flats; tidal channels; barrier sand spits; sediments; bedforms; biological communities; sedimentation; spit erosion; inlet channel migration; barrier evolution; Holocene

INTRODUCTION

Ohiwa Harbour is in south-eastern Bay of Plenty between Whakatane and Opotiki (Fig. 1). Physiographically the harbour is an estuarine lagoon (Davies 1977) enclosed by the Ohope and Ohiwa barrier spits. It covers 24 km^2 and is shallow, about 70% of its area is exposed at low tide (Paul 1966).

The adjacent Bay of Plenty coastline consists of a gently curved (concave seaward) beach backed by sand dunes and is interrupted only by the entrances to Tauranga Harbour and the rocky headlands of Town Point and Whakatane Heads (Fig. 1). Major rivers discharging onto this coastline in the vicinity of Ohiwa Harbour include the Tarawera, Rangitaiki, Whakatane, Waiotahi, and Waioeka. Only a few small streams enter directly into Ohiwa Harbour. The harbour catchment covers c. 200 km^2; 75% of the area is grass pasture, the remainder is forest and scrub (Table 1). The harbour itself is a popular recreational area for boating, water-skiing, and fishing; it contains large numbers of benthic

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Table 1 Some morphometric and hydrologic data for Ohiwa Harbour (based partly on Freestone (1976)).

Climate	
Mean annual air temp. (°C)	14.3
Mean annual rainfall (mm)	1321
Prevailing wind	N–NW
Drainage basin	
Land area (km^2)	172
Max. elevation (m)	371
Mean elevation (m)	~95
Forest and scrub cover (km^2)	43
Pasture cover (km^2)	129
Harbour characteristics	
Max. length (km)	9.2
Max. width (km)	5.7
Entrance width (km)	0.34
Max depth (m)	14
Mean depth (m)	~2
Perimeter (km)	~48
Harbour area (km^2)	24
Tidal flat area (km^2)	16.8
Vol. water (10^6 m^3)	
Low tide spring	11.4
High tide spring	49.4
Low tide neap	14.4
High tide neap	37.6
Tidal range (m)	
Spring tides	2.5
Neap tides	1.6
Entrance cross-sectional area (10^3 m^2)	
Low tide spring	1.568
Low tide neap	1.711
Tidal compartment (10^6 m^3)	
Spring tides	34.9
Neap tides	23.2

shell-fish, including commercially-farmed oysters near Ohakana Island. Significant residential development has occurred along Ohope spit.

This paper describes first the texture, composition, bedforms, and biological properties of modern sediments at Ohiwa Harbour and attempts to relate the sediment distribution to the general physical and biological processes operating in the harbour. It then discusses aspects of the late Holocene evolution of the Ohiwa barrier system, emphasising the very major morphological changes that have occurred in the vicinity of the harbour entrance in historical times.

METHODOLOGY

Ninety surficial sediment samples were obtained for compositional and textural analysis. Subtidal samples were collected with a modified dredge sampler (Davies-Colley 1976) designed to capture fines and recover the upper few centimetres of sediment. Intertidal flat, beach, dune, and spit samples were collected manually from the upper 2–3 cm of surficial sediment. Beach and dune profiles were made with an Elliot Automatic Profile Recorder NX12 which plots surface configuration at a 5:1 vertical exaggeration. Subtidal depths were measured with a Model DIR 60 Marlin echo-sounder.

All samples were washed to remove salts and wet sieved through a 4ϕ (0.063 mm) screen to separate the sand and mud fractions. Samples were treated with 100 vol. H_2O_2 and 1 M HCl to remove organic matter and carbonate respectively (Carver 1971). The coarser than 4ϕ size fractions (sand and gravel) were sieved for 15 min at ¼ϕ intervals, and mud fractions (finer than 4ϕ) were texturally analysed using a photocell hydrophotometer (Jordan et al. 1971). A cumulative frequency curve was plotted on linear probability paper for each sample and the Folk (1968) statistical parameters of mean size (Mzϕ), sorting ($\sigma_I\phi$), skewness (Sk_I), and kurtosis (K_G) were calculated by computer.

The bulk mineralogical composition of powdered, carbonate-free samples was analysed and semi-quantified by X-ray diffraction (XRD) techniques (Nelson & Cochrane 1970; Hume & Nelson 1982). Carbonate percentages were determined by weight loss following acidification. The percentages of quartz, feldspars, and carbonate in samples rarely totalled 100%. Therefore the remainder of the sediment composition was attributed to volcanic glass and minor amounts of heavy minerals, a procedure confirmed by microscopic examination of 12 random samples. The clay mineralogy of the less than 2 µm size fraction of 12 muddy samples was determined by XRD from oriented mounts prepared using the dropper-on-glass-slide technique (Hume & Nelson 1982). Crystalline clay minerals were identified after analysis of air-dried, glycolated, and heated (550°C for 1 h) mounts (Carroll 1970). The presence of allophane in the clay fraction was confirmed by treating samples with a saturated solution of sodium fluoride and a phenolphthalein indicator (Fieldes & Perrott 1966). Magnetically susceptible minerals in the 2–4ϕ size fractions were concentrated with a Frantz magnetic separator, mounted on glass slides, identified petrographically, and their abundances determined by counting 200 grains.

Tabulated results of all textural and compositional analyses are given in Richmond (1977).

GEOMORPHOLOGY

Briefly, the dominant geomorphic features at Ohiwa include the following:

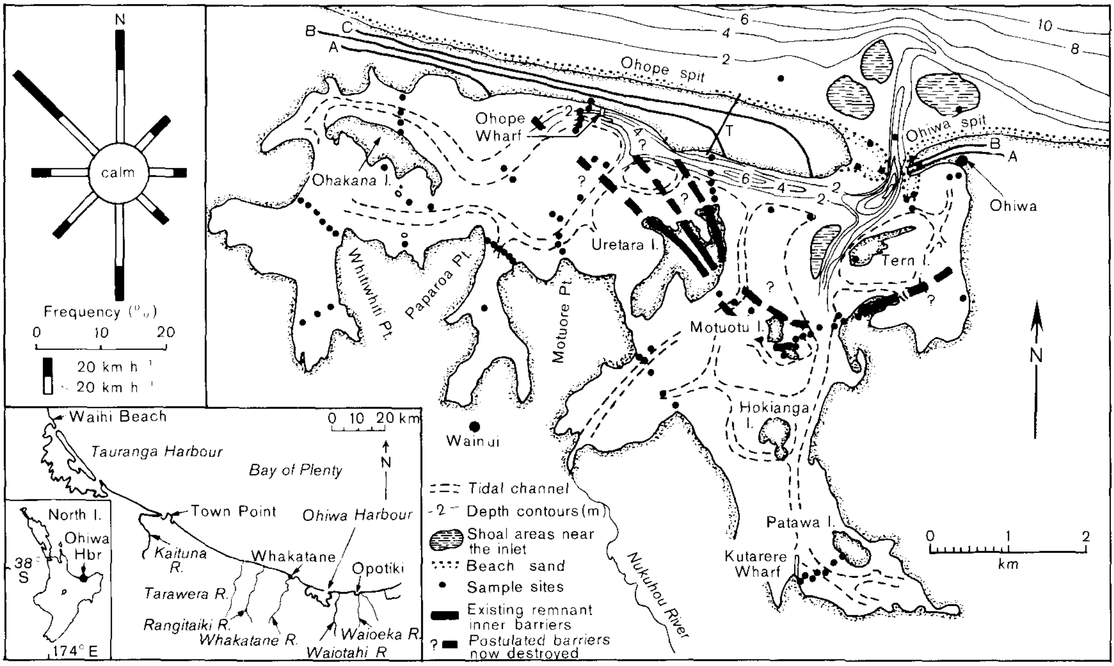

Fig. 1 Locality maps, generalised bathymetry, and sampling sites for Ohiwa Harbour. The lines labelled A, B, and C mark the approximate positions of shore lines at about the time of the Taupo Pumice (AD 131), Kaharoa Ash (AD 1020), and Tarawera Ash (AD 1886) eruptions respectively (Smith 1976; Gibb 1977). Line T is transect position shown in Fig. 3. Wind data are for nearby Whakatane Aerodrome from 1960–1964 (New Zealand Meteorological Service 1960–1964).

a) *Ohope barrier spit* is "drumstick" shaped, 6 km long, and varies in width from 300–1000 m (Fig.2). A pronounced feature of the spit is a series of 6 or more subparallel dune ridges which recurve towards the harbour at their distal (eastern) end, similar to those described by Marks & Nelson (1979) on Omaro spit, Coromandel Peninsula. On passing inland the dune ridges gradually increase in elevation to 15 m above mean high water mark (MHWM); their dune form becomes progressively more irregular with stabilised blow-outs common (Fig. 3). Apart from the presently forming foredune ridge, the dunes are well stabilised by vegetation, mainly *Spinifex, Ammophila* (marram grass), and *Lupinus* (lupin). The distal terminus of the spit is periodically flooded during spring tides and storms, and consists of isolated, sparsely vegetated, low (c. 2 m), hummocky dunes separated by broad sand flats (Fig. 2). The harbour side of the spit typically exhibits an erosional scarp up to 2 m high truncating earlier barrier deposits.

b) *Ohiwa spit*, east of the harbour entrance (Fig. 4), is much smaller and consists of 1 major dune ridge (up to 10 m high) currently undergoing active erosion. The distal end is of low relief (< 1.5 m) and is the site of a former township (see below).

c) The *harbour entrance* (Fig. 4) shows many of the features common to sandy tidal inlets (e.g., Hubbard et al. 1979; Hayes 1980). The ebb tidal delta contains well developed entrance shoals (swash bars) and channel margin bars. The main channel reaches a maximum depth of 14 m at its narrowest point where it is c. 300 m wide. The flood tidal delta is poorly defined and is closely associated with the confluence of the 2 main tidal channels.

d) *Intertidal flats* in the harbour are extensive (17 km^2), broad, low relief (< 1 m), gently sloping (< 3°) platforms that are elongated parallel with the main channels. Lower tidal flats (c. 60% of intertidal zone) are dissected by meandering intertidal run-off creeks (Fig. 5). Upper tidal flats are dissected only by streams that originate on land or in salt marshes. Over much of the harbour the upper flats abut against cliffs or road escarpments. Locally, particularly in the distal portions of the southern embayments of the harbour, they merge around MHWM with salt marsh areas dominated by *Salicornia, Juncus*, and *Leptocarpus*. Some upper tidal flat areas are covered by moderately dense stands (5–25% coverage) of 1–2.5 m tall mangroves (*Avicennia resinifera*).

Fig. 2 Oblique aerial photograph looking west along Ohope spit towards Whakatane Heads. Note the sparsely vegetated sand flats forming the distal terminus of the spit, the ocean beach sands passing abruptly inland into a vegetated dune ridge complex (Fig. 3), and the remnant barrier flat deposits abutting Ohiwa Harbour.

e) *Beaches* within the harbour form less than 10% of the perimeter and vary widely in profile and plan form. The majority are very narrow (< 15 m) and moderately steep (6–7°), and include the harbour-side beach of Ohope spit, beaches associated with minor sand spits on Ohakana and Hokianga Islands, and pocket beaches about the islands and southern embayments.

f) *Subtidal channels* mainly trend roughly north-south, following the 4 drowned, probably fault-controlled, river valleys which give the harbour its digitate shape (Fig. 1). The largest channel, however, trends east-west and is immediately adjacent to, and parallel with, the Ohope barrier spit.

g) *Islands* within Ohiwa Harbour consist predominantly of consolidated Pleistocene Huka Group deposits (Healy et al. 1964), but Tern and Motuotu Islands are low sand cays composed of modern sediments. Tern Island is an isolated remnant of the former Ohiwa spit (see Fig. 12).

HYDROLOGY

Table 1 presents some physical and hydrologic characteristics of Ohiwa Harbour. The semi-diurnal tides reach a maximum range of 2.5 m. The small ratio (c. 0.7) of the total volume of harbour water to the spring tidal compartment shows that flows are completely dominated by tidal currents (Heath 1976), a conclusion supported by tidal gauging at the inlet where surface speeds of 125 cm s^{-1} have been measured (Freestone 1976). Current measurements over a tidal cycle for stations in the inlet channel and in a small tidal creek are illustrated in Fig. 6. The residence time for water in the harbour is calculated, using Heath's (1976) method, to be only 1–2 tidal cycles. The small freshwater inflow of about 1.2 $m^3 s^{-1}$ (Freestone 1976) does not significantly alter this rapid flushing time.

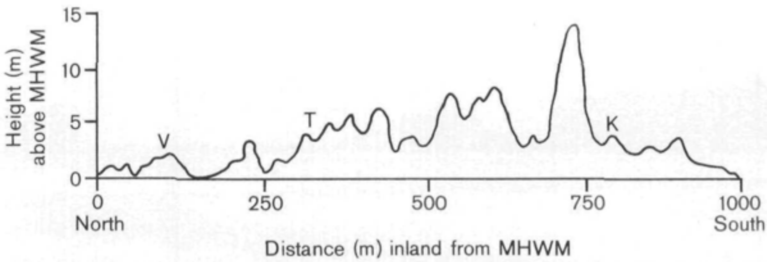

Fig. 3 Profile across the dune ridge topography of Ohope barrier spit showing also the approximate seaward limits of vegetation (V), Tarawera Ash (T), and Kaharoa Ash (K). Transect located on Fig. 1. Vertical exaggeration ×16.

Fig. 4 Oblique aerial photograph looking southwest across the inlet channel to Ohiwa Harbour. Ohiwa spit is in left foreground with Tern Island and Motuotu Island behind. The distal terminus of Ohope spit is at right centre. Note the line of iron rails (dark) and the dumped car bodies along the ocean-side of Ohiwa spit, part of the coastal protection works attempted by local residents.

Little is known about the Bay of Plenty ocean wave climate (Pickerell & Mitchell 1979). Harris et al. (1983) indicate a south-eastwards moving wave-induced littoral drift for the western Bay of Plenty and a southwestwards drift for the eastern side. Waves within the harbour result from local winds, principally from the north to northwest and the south (Fig. 1). The short fetches result in steep choppy waves, rarely exceeding 0.5 m in height.

SEDIMENT TEXTURE

Surficial sediments at Ohiwa are dominated by fine sands (Fig. 7). Non-carbonate gravel-sized sediments are generally rare, but locally important contributions occur in upper tidal flat, harbour beach, and spit environments wherever a local cliff source exists. Mud-bearing (dominantly silty) sands are more common in harbour environments away from the entrance.

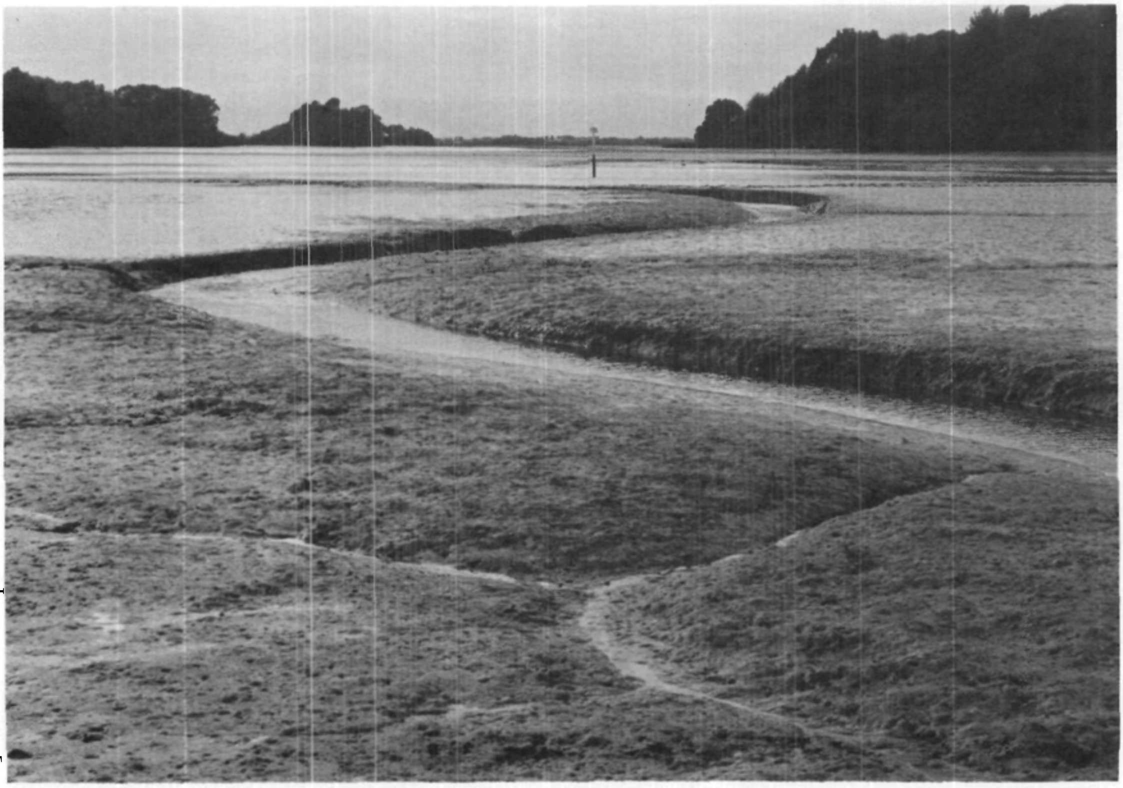

Fig. 5 Typical tidal channel heirarchy at Ohiwa Harbour. Small V-shaped tidal creeks join a larger flat-bottomed tidal creek having a meander wavelength of about 60 m which drains ultimately into a major subtidal channel in the background. Note the extensive biological reworking of the lower tidal flats, in this instance mainly by the burrowing crab, *Helice crassa*.

The range and mean values for mean grain size (Mzϕ), standard deviation ($\sigma_I\phi$), and skewness (Sk_I) for sediment samples from the various depositional subenvironments at Ohiwa are presented in Fig. 8. The ability to distinguish readily between subenvironments on the basis of sediment grain size characteristics appears limited. However, by considering the parameters together, particularly mean size and sorting (e.g., Doeglas 1968; Buller & McManus 1975), the modern deposits can be grouped into 2 general lithofacies (Fig. 8 and 9): (a) Lower harbour lithofacies — well sorted, medium to fine sands with negatively-skewed or near-symmetrical distributions are characteristic of barrier beach, dune, entrance shoal, and channel deposits, and are consistent with deposition under generally high energy conditions; and (b) Upper harbour lithofacies — poorly to very poorly sorted, mainly positively-skewed, fine to very fine sands (commonly silty) over the remainder of the estuary, and indicative of deposition under more variable, but generally low energy conditions. The coarser of the upper harbour lithofacies occur in channel and harbour beach deposits and the finer in intertidal flats, creeks, and channel bank subenvironments.

SEDIMENT COMPOSITION AND PROVENANCE

Terrigenous components

Harbour sediments are relatively homogeneous in their bulk composition (Table 2) and are dominated by volcanic glass and pumice fragments (av. 45%), feldspar (av. 30%, plagioclase > > potash feldspar), quartz (av. 20%), and biogenic carbonate (av. 5%, aragonite > > calcite). Lower harbour sediments tend to be relatively enriched in quartz and feldspar and depleted in glass compared to upper harbour sediments, possibly reflecting selective transport of the lighter glassy fragments away from the high energy entrance area. Trace amounts (< 2%) of opaque and ferromagnesian minerals occur, typically in the following relative abundances: titanomagnetite/ilmenite > > green-brown

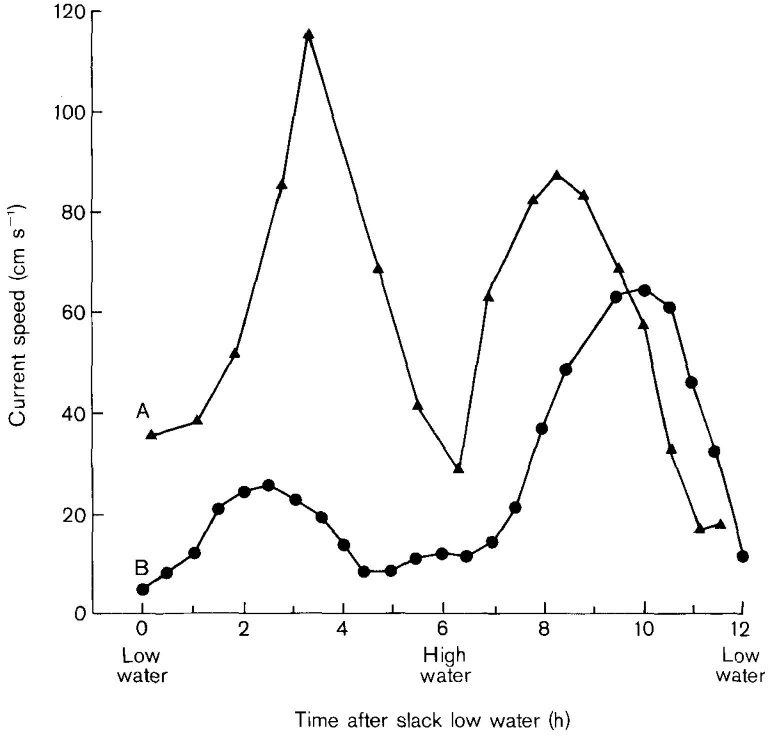

Fig. 6 Variation in surface current speeds over a tidal cycle at Ohiwa Harbour near the middle of the harbour inlet channel, **A**; and in a small tidal creek on the Kutarere arm of the harbour, **B**. Data for A from Freestone (1976).

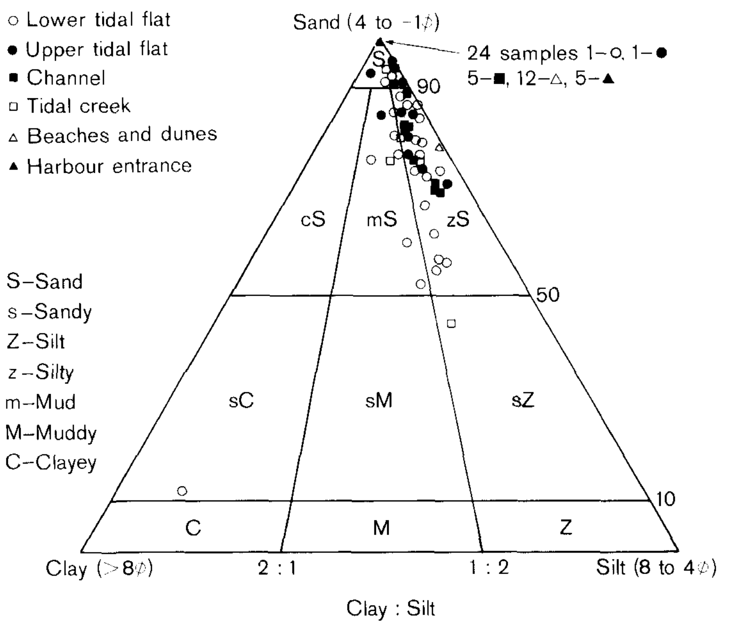

Fig. 7 Textural classification (after Folk 1968) of surficial sediments from the major depositional environments at Ohiwa Harbour.

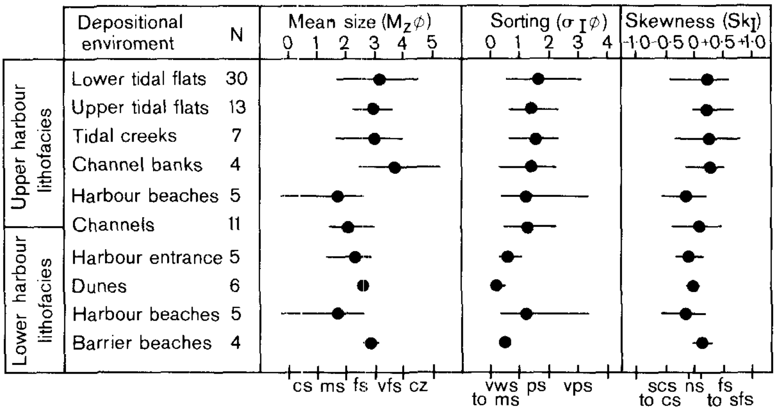

Fig. 8 Variations in the mean and range of values for grain-size parameters of surficial sediments from the various depositional environments at Ohiwa Harbour. Abbreviations for mean size: cs, coarse sand; ms, medium sand; fs, fine sand; vfs, very fine sand; cz, coarse silt; for sorting: vws to ms, very well to moderately sorted; ps, poorly sorted; vps, very poorly sorted; for skewness: scs to cs, strongly coarse- to coarse-skewed; ns, near-symmetrical; fs to sfs, fine- to strongly fine-skewed.

hornblende > hypersthene ⩾ pale green hornblende (cummingtonite) > augite ⩾ biotite. The dominance of plagioclase over quartz, the high glass and pumice content, and the abundance of titanomagnetite, amphiboles, and pyroxenes in the heavy mineral fraction of sediments indicate the dominance of an acid volcanic provenance. The tephra mantle in the Ohiwa catchment (Howorth 1975) is an obvious local source, but the extremely limited harbour catchment of only 7 times the harbour surface area precludes it being the dominant one. Most important is the adjacent oceanic littoral zone whose sediments are of similar composition and have clearly been shown by Healy et al. (1977) and Healy (1978) to have been derived ultimately from the major rivers draining the Central Volcanic Region (Fig. 1).

Greywacke gravels occur locally on those harbour beaches adjacent to conglomeratic outcrops of Pleistocene Huka Group sediments and represent lag materials from sea-cliff erosion.

The small content of clay minerals in the mud fraction consists of allophane and (meta-) halloysite, probably eroded from catchment rhyolitic tephras (Howorth 1975; Kirkman 1975), and illite, chlorite-vermiculite mixed-layer clay, and some kaolinite, compatible with an origin from greywacke-derived Quaternary sediments and soils (e.g., Fieldes 1968; Hume 1978), also in the catchment.

Biological components and their effects on sedimentation

Ohiwa Harbour and environs support rich biological communities (Fig. 10) which act to supply, stabilise, and rework sediments (Table 3). Most of that supplied is in the form of aragonitic shell material, up to 95% of certain deposits, but includes widespread organic matter in floral remains and faecal matter, forming as much as 5% by weight of the muddier sediments. Paul (1966) estimated the standing crop of cockle (*Chione stutchburyi*) and pipi (*Amphidesma australe*) at 750×10^6 and 100×10^6 individuals respectively. Large intertidal shoals opposite the Ohope wharf support a thick (up to 1 m) mantle of shell debris, dominated by cockles (Fig. 11). Many of the channel bottoms are shell lagged.

Sediment stabilisation occurs by sediment binding through organisms attaching themselves to the substrate (i.e., root systems and byssal threads) and by current baffling. The fauna are prolific substrate reworkers as evidenced by the almost complete lack of preserved physical sedimentary structures within the sediments. A conspicuous shell layer 20–30 cm below the intertidal surface consists of whole and broken, generally non-abraded shell fragments. The layer probably formed through concentration of shells by faunal reworking and represents the approximate depth limit of intense biogenic activity (Trewin & Welsh 1976).

BEDFORMS AND SEDIMENTARY PROCESSES

Bedforms were examined in all intertidal areas at Ohiwa and subtidally at the inlet. Bedforms were mainly poorly developed or absent where the mud content of bottom sediments exceeded about 10% by weight and/or where filamentous algal mats occurred. They were classified on the basis of their wavelength following Boothroyd & Hubbard (1974): ripples < 60 cm, megaripples 0.6–5 m, and sandwaves > 5 m.

Both wave and current ripples occur. Wave ripples are characterised by linear crests with occasional bifurcations and symmetrical to slightly asymmetrical profiles with sharp crests and rounded troughs. Typical tidal flat wave ripple dimensions are: height 1.5 cm, wavelength 6 cm, and a ripple

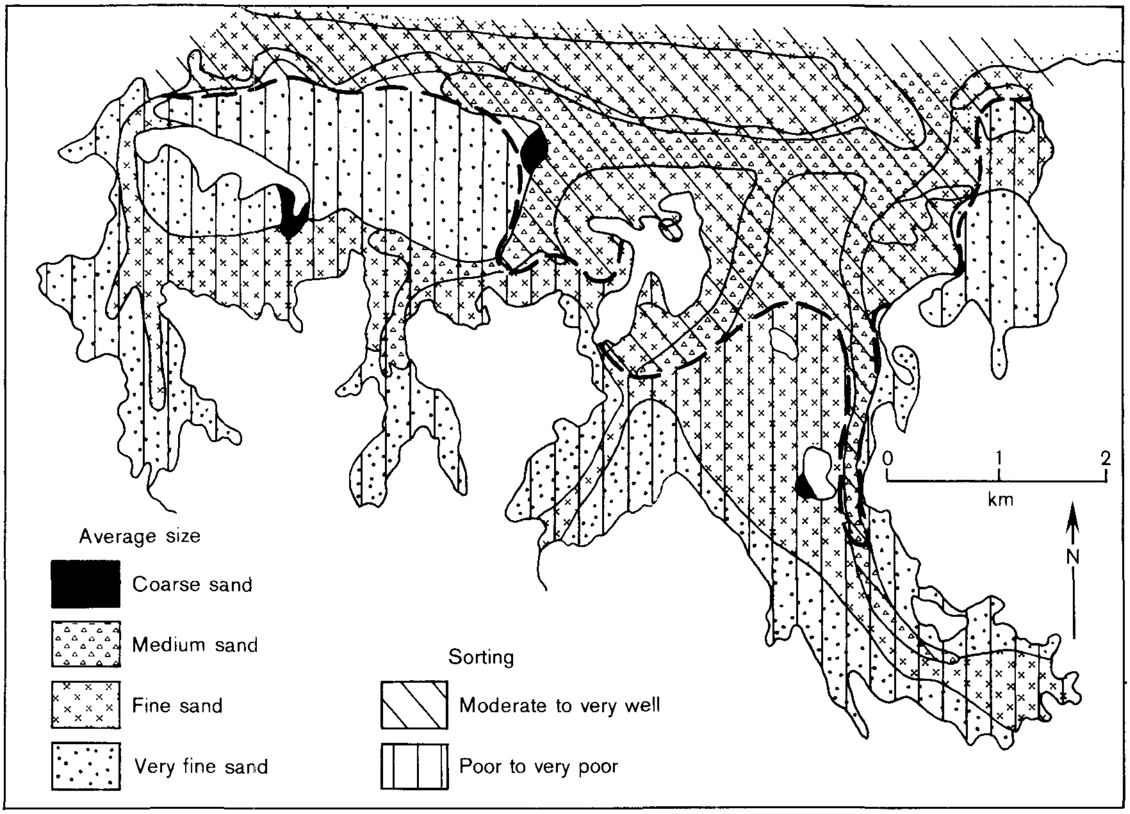

Fig. 9 Simplified surficial sediment facies map for Ohiwa Harbour based on the average grain size and sorting (see Fig. 8 for definitions) of sediment samples along the lines advocated by Doeglas (1968) and Buller & McManus (1975). The bold dashed line separates roughly the lower and upper harbour lithofacies (see Fig. 8).

index of 4. The orientation of wave ripple crests is predominantly subparallel to shore because of wave refraction.

Current ripples of various types are ubiquitous at Ohiwa. Linear to sinuous crested current ripples are common on many of the tidal flat surfaces, and can be difficult to distinguish from asymmetrical wave-formed ripples (e.g., Tanner 1967; Reineck & Singh 1973; de Raaf et al. 1977). The majority of current ripples are of the three-dimensional type with dimensions in the range 1–5 cm for height and 8–20 cm for wavelength (ripple index 4–15). Lunate and linguoid ripples are the dominant forms in the intertidal run-off creeks and are also found in the larger subtidal channels, both singly and superimposed on larger bedforms. In the run-off creeks they are mainly ebb-oriented because during receding tides water is channelled into the creeks whereas on flooding tides the water level tends to rise as a sheet. As water level drops in the creeks, the three-dimensional ripples are bevelled somewhat and approach a rhomboidal crest pattern. The subtidal current ripples reverse orientation with each tide.

Ebb- and flood-oriented sinuous and three-dimensional megaripples are widespread in the subtidal channel bottoms and, in a few areas, are subaerially exposed at low tide, notably on the flood tidal delta. Here the megaripples are up to 30 cm high with an average wavelength of 3.2 m and during the study period were always observed to have a flood orientation, even after periods of ebb flow.

Well developed sand wave fields are subaerially exposed at low tide on the lower margins of the flood tidal delta and bordering major channels. Crest patterns varied from straight to gently curved with wavelengths from 6–10 m and heights of 20–30 cm. During subaerial exposure these sand waves still retain their flood orientation, but are covered by ebb-oriented three-dimensional ripples. During

Table 2 Average bulk mineralogical composition (range in brackets) of samples from the major depositional environments at Ohiwa Harbour.

	N	Quartz	Feldspar[4]	$CaCO_3$[5]	Others[6]
Tidal flats[1]	43	18 (5–30)	32 (15–60)	4 (0–93)	46 (15–75)
Tidal channels[2]	24	17 (10–30)	33 (12–58)	8 (1–36)	42 (0–75)
Beaches[3]	12	20 (7–30)	41 (26–62)	tr (0–5)	38 (18–45)
Dunes	6	20 (14–29)	23 (18–28)	tr (0–2)	56 (54–64)

1. Includes lower and upper flats.
2. Includes tidal creeks and channel banks.
3. Includes harbour and barrier beaches.
4. Plagioclase > > potash feldspar.
5. Aragonite > > calcite.
6. Mainly volcanic glass and pumice, but also minor clay and heavy minerals.

receding tides these transverse bedforms redirect water movements parallel to their crests towards the channels. Fathometer records indicated well developed sand waves occurred in the main channels and inlet troughs, but no monitoring was done to check for crestal patterns or orientation reversals through tidal cycles.

The dominance of tidal flows over fluvial or wave processes at Ohiwa is indicated by the low freshwater input from the surrounding catchment (only 0.2% of tidal prism), the large tidal prism compared to residual low tidal volume (Table 1), the tide-dominated inlet morphology (e.g., Hubbard et al. 1979; Hayes 1980), and the character, distribution, and orientation of major bedforms (see above). However, relative energy levels decrease on passing up harbour (Fig. 6) and from the channel confines out on to the adjacent tidal flats. In consequence, there is an overall up-harbour decrease in sand content and mean grain size of bottom sediments (Fig. 7–9), in the degree of sorting of sediments (Fig. 8 and 9), and in the scale of bedforms.

The modern sediment distribution at Ohiwa Harbour is a function of complex interactions between current, wave, and biological processes (Table 4). Although quantitatively there remain many questions to be answered, the dominant sedimentary characteristics and their spatial and temporal distributions are at least qualitatively understood for each of the modern sedimentary subenvironments at Ohiwa.

HARBOUR ENTRANCE CHANGES

Holocene tephra distributions, historical survey data, and air-photo interpretations indicate that Ohope spit has migrated eastwards during the late Holocene at the expense of Ohiwa spit. Comparison of the original 1868 survey map with a 1945 air photograph shows an easterly migration of c. 315 m, or 4.09 m y^{-1} for the distal end. From 1868–1974 the rate is slightly less at 272 m, or 2.6 m y^{-1}. This discrepancy is caused by erosion of the distal end of the spit from 1945–1974.

During the late 1800s an hotel was built on Ohiwa spit (Fig. 12). In 1867 the hotel was surveyed as 1.5 chains from MHWM. During the early 1920s 3 blocks of duneland around the hotel were subdivided into the first Ohiwa township. By the late 1920s, the township and hotel were abandoned beause of erosion problems. Severe storms in the 1930s eroded away much of the spit and by 1938 the site of the former front street was occupied by a tidal channel separating the spit from Tern Island, formerly part of the spit.

In 1949 a new subdivision was sited further east towards the base of the spit, but it soon became evident that this region of the spit was also eroding. Accelerated erosion of the foredunes occurred during the *Wahine* storm on 10 April 1968, at which time heavy northerly seas pounded the coast. Further episodes of erosion occurred in November–December 1968 during northerly gales. From December 1969 to February 1970 an iron-rail and manuka protection wall was constructed parallel to the foredune in the intertidal zone (Fig. 4). Erosion has continued despite additional stabilisation attempts by concerned residents who deposited old car bodies and blocks of concrete at the base of the foredune. Erosion climaxed with severe property loss in April 1976.

Survey data and air photograph analysis

The original 1867–1868 hydrographic survey, and shore-line surveys of 1876, 1882, 1914, 1949, 1958, 1961, and 1976, as well as aerial photographs for the years 1945, 1965, 1971, and 1974 (Smith 1976; Healy et al. 1977), have been used to investigate inlet changes (Fig. 12).

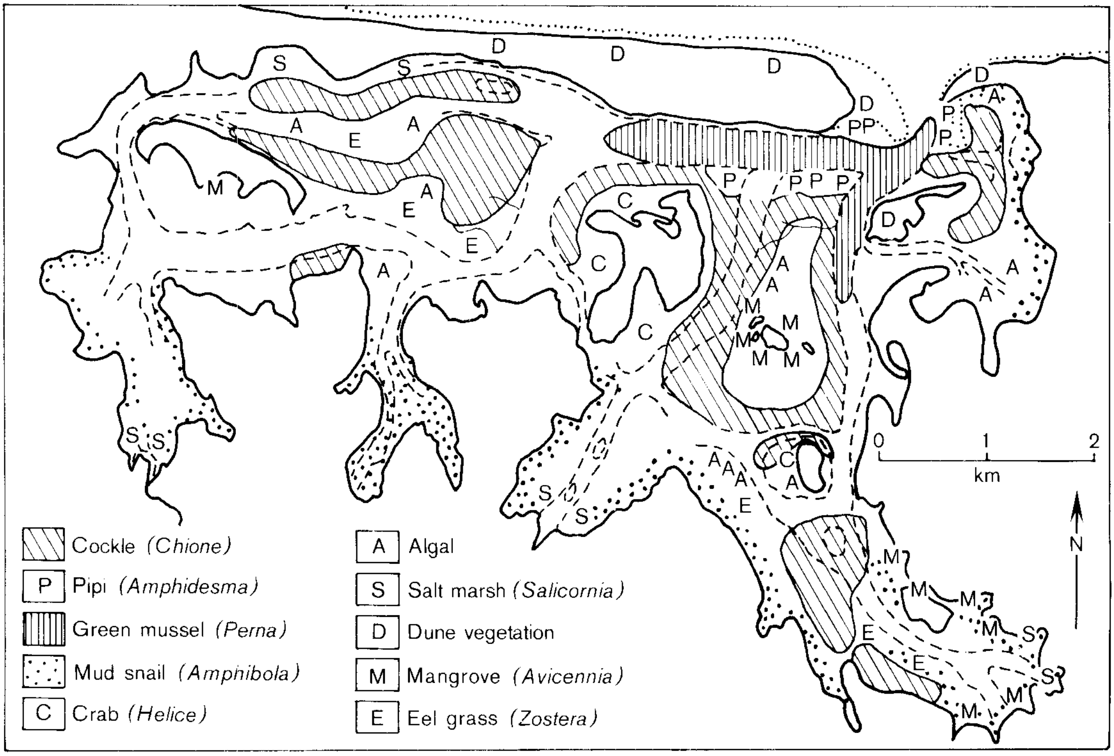

Fig. 10 Distribution of the major biofacies (see Table 3) at Ohiwa Harbour (adapted from Paul 1966 and Bioresearches Limited 1975).

Changes of MHWM on the ocean beach of Ohope spit are summarised from 2 sites (Table 5). Both sites have undergone erosion followed by accretion after about 1960. Marked accretion (c. 90 m) occurred towards the distal end of the spit, the cuspate foreland developing where the ebb-tidal delta joins to the spit.

In contrast, Smith (1976) showed that the ocean beach at Ohiwa spit experienced a period of accretion of some 150–170 m from 1867–1911. The period 1911–1949 was dominated by erosion and the beach retreated approximately to its 1882 position. After 1949, and for the next decade, the beach accreted by c. 100 m. From 1959–1976 there has been marked erosion of the beach and retreat of the sand dunes. Erosion appears to have exceeded 200 m in places and the shore-line retreat extended eastwards to include Waiotahi spit (Healy et al. 1977).

The distal spit tips have also changed markedly. Ohiwa spit retreated continually eastwards (Table 6); rapid from 1867–1876, somewhat slower until 1959, and accelerated until 1976. At Ohope spit the ocean-beach side eroded severely in 1965 but had accreted markedly by 1974. Net erosion also occurred along the inner part of the spit, probably as a result of harbour waves and lateral migration of the main tidal channel.

The areal extent of erosion and deposition in the vicinity of the entrance has been determined for the period 1945–1974 (Table 7). The results show net land loss on Ohiwa spit of 86 000 m^2, and net accretion on Ohope spit of 102 000 m^2. Although these areas differ, the volume of sand involved may not be appreciably different as the accretionary dunes on Ohope spit are much lower than the frontal dunes being eroded on Ohiwa spit.

In summary, there is clearly long term migration of the channel towards the eastern perimeter of the harbour consequent upon the forcing action of an eastward net littoral drift, with erosion of the Ohiwa spit and accretion on Ohope spit. The geomorphology of parallel dune ridges on Ohope spit, each showing sequential recurvature at their distal end, is clear evidence that the spit has been growing predominantly eastward rather than seaward during its development in the late Holocene. Moreover, the nearby Whakatane River to the west, and

Table 3 Major characteristics of the dominant biofacies at Ohiwa Harbour (based partly on Paul (1966) and Bioresearches Limited (1975)).

Biofacies	Dominant (*) and associated species	Preferred environment	Preferred substrate	Major effects on sedimentation
Cockle	*Chione stutchburyi** *Macomona liliana* *Mactra ovata*	Widespread in middle-lower tidal flats	Silty sands	Suspension feeders, bioturbate sediment (top 5 cm), contribute in situ and transported shell carbonate and faeces, support variety of epifauna (e.g., *Anthopleura aureoradiata, Eliminius modestus, Modiolus neozelanicus*, and algae)
Pipi	*Amphidesma australe**	Middle-lower tidal flats near entrance	Clean sands	Suspension feeders, bioturbate sediment (top 15 cm), contribute mainly transported shell carbonate, support epifauna (as above)
Green mussel	*Perna canaliculus**	Channels near entrance	Clean sands and shells	Suspension feeders, bind substrate with byssus threads, contribute shell carbonate and faeces
Mud snail	*Amphibola crenata** *Cominella glandiformis* *Zeacumantus lutulentus* *Z. subcarinatus* *Zediloma subrostrata* *Potamopyrgus antipodarum*	Upper-middle tidal flats in southern reaches	Silty sands	Deposit feeders, bioturbate surface, some burrowing, faecal strings
Crab	*Helice crassa** *Macrophthalmus* sp.	Upper-middle tidal flats	Silty sands	Burrow and rework sediment to depths of 25 cm
Mangrove	*Avicennia resinifera** *Elminius modestus* *Helice crassa* Algae	Widespread on upper-middle tidal flats	Silty sands	Baffle water motion, stabilise and trap sediment, contribute organic matter
Salt marsh	*Salicornia australis** *Selliera radicans* *Samolus repens* *Helice crassa*	Restricted distribution on upper tidal flats and above	Silty sands, peaty	Baffle water motion, stabilise and trap sediment, contribute organic matter
Dune vegetation	*Desmoschoenus spiralis** *Spinifex hirsutus** *Lupinus arboreus* *Coprosma acerosa* *Muehlerbeckia complexia* *Arundo conspicna* *Leptospernum* sp.	Aeolian on barrier spits	Clean sands	Baffle wind currents, rhizomes stabilise and trap sand, promote soil development
Algal	*Enteromorpha* sp.* *Ulva lactuca** *Gracilaria secundata*	Below upper tidal flats	Silty sands	Some stabilisation and trapping of sediment, supply organic matter
Eel grass	*Zostera capricorni** *Chione stutchburyi* *Helice crassa*	Widespread but not dense mats below middle tidal flats	Initially clean sands	Baffle water motion, stabilise and trap sediment, contribute organic matter

Fig. 11 Shell bank, dominated by the cockle *Chione stutchburyi*, on tidal flats opposite Ohope Wharf. Valves are reworked by current action from the adjacent lower tidal flats and concentrated in semi-permanent shoal deposits, especially common in the northern portions of Ohiwa Harbour.

the Waiotahi River to the east, both possess barrier spits deflected eastward, and these rivers enter the sea at the eastern extremity of the embayments. Evidence from elsewhere in the Bay of Plenty also indicates that littoral drift as far east as Ohiwa Harbour is from the northwest (Wallingford Report 1963; Gibb 1977; Healy et al. 1977; Harris et al. 1983).

Evidently, erosion of Ohiwa spit is long term, and at the average rate of inlet migration of 2.75 m y^{-1} (Table 6), the tidal entrance to Ohiwa Harbour could abut against bedrock on the eastern side of the harbour within 250 years. However, if the accelerated inlet migration rate of 7.7 m y^{-1} evident from 1959–1976 is maintained, then Ohiwa spit could be destroyed in as short a time as 90 years.

HOLOCENE EVOLUTION OF OHIWA BARRIER SYSTEM

Both Smith (1976) and Gibb (1977) present aspects of the late Holocene history (c. 2000 y BP to present) at Ohiwa based on tephrochronological evidence. For the adjacent Whakatane graben a detailed chronology of Holocene sedimentation is presented by Pullar & Selby (1971). They showed that some 3 km of dune progradation had occurred by 3230 BC, as dated by the Whakatane Ash. Ensuing tephra marker beds indicate that progradational rates were not uniform and were maximum (c. 4 m y^{-1}) between about 750 BC (Whakaipo Ash) and AD 131 (Taupo Pumice). This may have been because of a falling sea level at that time (Pullar &

Table 4 Major sedimentologic characteristics of the modern subenvironments occurring at Ohiwa Harbour.

Sedimentary environment	Dominant bedforms	Dominant sediment	Biological effects	Sedimentary processes
Barrier spit				
Dunes	Linear ripples	Well sorted fine sands	Stabilised by vegetation	Aeolian
Beaches	Rhomboid ripples	Well sorted fine sands	Some reworking in swash and near-shore zone	Wave swash-backwash, some aeolian
Intertidal zone				
Upper tidal flats	Linear wave ripples	Poorly sorted fine to very fine sands	Reworked by snails and crabs; stabilised by mangrove and salt marsh plants	Mainly small amplitude waves
Lower tidal flats	Wave, current, and combination ripples	Poorly sorted fine sands to coarse silts	Reworked by cockles, pipis, snails, and crabs; stabilised by eel grass, mangroves, and algae	Combination current and wave activity
Tidal creeks	Linguoid ripples and rhomboid ripples	Well sorted medium sands to poorly sorted fine sands	Little biological activity	Dominated by ebb currents
Channels	Linguoid ripples, sinuous to lunate megaripples, and linear to sinuous sand waves	Moderately well sorted medium to fine sands	Some stabilisation by mussels and cockles	Strong current activity, both ebb and flood
Flood-tidal delta	Linear to linguoid ripples, sinuous megaripples, and linear sand waves	Well sorted fine sands	Some reworking by pipis	Dominated by flood currents, also small amplitude waves

Selby 1971), enhancing barrier and lagoon formation. Although rates of shoreline progradation subsequently decreased (c. 0.5–1.2 m y^{-1}), the actual volumes of sand deposited in the coastal barrier-dune system appear from Pullar & Selby's (1971) fig. 1a, b to have been substantially greater than before, especially after the Taupo pumice eruption of AD 131, with more significant vertical accretion of the dune complex. In all, some 9.75 km of progradation has occurred over the last 8000 y, most of the sedimentary material being derived from the adjacent Volcanic Plateau.

Field work to date has so far failed to identify a parallel sedimentation history in the Ohiwa embayment but, as discussed below, the events in the Whakatane graben immediately updrift have probably exerted a considerable influence on the evolution of Ohiwa Harbour. Major events are inferred as follows:

1. At the height of the last glacial maximum the Ohiwa catchment comprised a number of rivers draining northwards to a base level at least 100 m lower than present. The rapid post-glacial sea-level rise flooded the river valleys, inducing sedimentation.
2. Ohiwa Harbour is a relatively shallow indentation in the general alignment of the Bay of Plenty coast with 4 distinct valleys of small catchment size. Geomorphic evidence and air photographs reveal the existence of a remnant inner barrier system in the central sector of the harbour (Fig. 1) which possibly formed a spit across the largest valley entering the harbour. Although detailed investigations have not been carried out, these inner barriers possibly formed from littoral sand movement at about the time that post-glacial sea level attained, or was a little above, its present position some 4000–5000 years ago (Schofield 1975; Gibb 1977; Marks & Nelson 1979). At this time the present Ohope and Ohiwa spits were not in existence, but the Ohiwa embayment would have been infilling.
3. About 2000 years ago the sedimentation regime in the Ohiwa embayment dramatically altered. This may have been associated with a small but abrupt

Table 5 Shore-line changes (m) on the ocean beach side of Ohope spit, 1868–1976, based on survey data of the MHWM. Negative and positive values indicate sediment erosion and accretion respectively (after Smith 1976).

		1868–1958	1958–1976	Net change
Site 1	Erunui Road	−58	+50	−8
		1868–1961	1961–1976	Net change
Site 2	Directly north of trig. point 6981 (c. 1.5 km from end of spit)	−45	+92	+47

lowering in sea level (Schofield 1975; Marks & Nelson 1979). However, at Ohiwa it was clearly also associated with a sudden and substantial increase in the supply of littoral sediment. We suggest that this sediment originated updrift from the adjacent Whakatane graben. Prior to c. 2000 years BP the deep re-entrant of the Whakatane graben had been infilling and acting as a trap for the sediment carried by the major Tarawera, Rangitaiki, and Whakatane Rivers, as well as that supplied alongshore by the net eastward littoral drift (Healy & Kirk 1982). By c. 2000 years ago the re-entrant became largely infilled, and the huge volumes of fluvially-derived, volcanogenic sediments no longer had favourable refracted-wave conditions in which to form progradational parallel dune ridges. This caused significant changes to sedimentation patterns along the Rangitaiki Plains coast. Whereas all the innermost subaerial sedimentation in the Whakatane graben developed as concave-seaward parallel dune ridges, the 1 km wide belt of dunes fronting the coast consists of high, irregularly parabolic, transgressive blowout dunes advancing inland. The latter all post-date the AD 131 Taupo Pumice eruption (Pullar & Selby 1971, fig. 1a, b) and since about that time it is postulated that much of the oversupply of sand in the littoral zone moved eastwards around Whakatane Heads infilling Ohiwa Harbour and forming the Ohope-Ohiwa barrier spits. Healy (1978) has demonstrated that drift around Whakatane Heads and along Ohope Beach is continuing at present.

This differs from Gibb's (1977) inference that the sediment source for the barrier system was from the erosion of the Whakatane and Waiotahi headlands as depicted in his fig. 1a, b. There is no evidence to support landmass extensions 2–3 km seawards of the present coastline on both sides of the Ohiwa embayment about 4600 BC. Moreover, Chappell (1975) has shown that this sector of the eastern Bay of Plenty has probably uplifted by 1–2 mm y^{-1} throughout the Holocene, enhancing the expectation that any such landmass would be preserved.

Table 6 Distance and rate of eastwards retreat of the distal tip of Ohiwa spit based on survey data of the MHWM from 1867–1976 (after Smith 1976).

Period	Retreat (m)	Rate (m y^{-1})
1867–1876	−80	−8.9
1876–1959	−90	−1.1
1959–1976	−130	−7.7
1867–1976	−300	−2.75

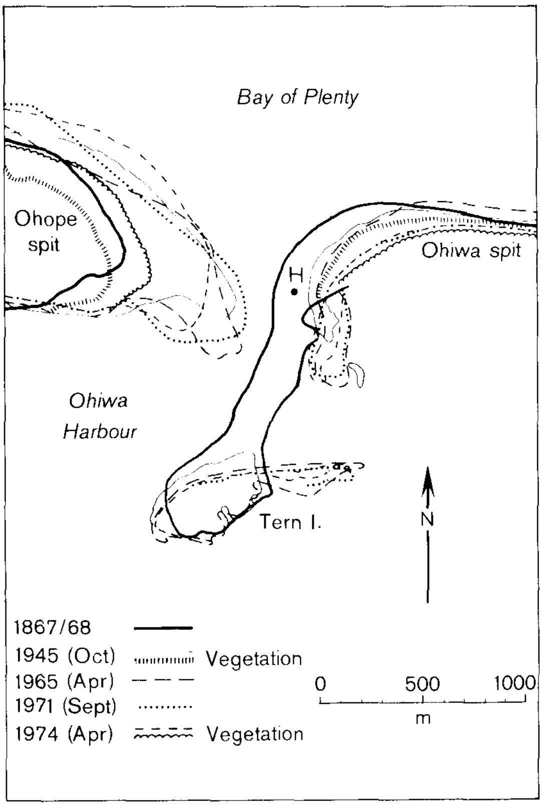

Fig. 12 Inlet changes at Ohiwa Harbour from 1867–1974 based on original hydrographic survey data (1867–1868) and analysis of twentieth century air photographs. H is the position of the former Ohiwa hotel.

Table 7 Net inlet changes based on interpretations of air photographs (1945, 1965, 1971, and 1974). Negative and positive values indicate retreat (erosion) and advance (accretion) respectively.

	Ohiwa spit	Ohope spit
Maximum ocean beach change (m)	−126	+127
and rate (m y^{-1})	(−4.3)	(+4.4)
Inlet migration (m)	−87	+70
and rate (m y^{-1})	(−3.0)	(+2.4)
Movement of the ocean beach vegetation line (m)	−143	+203
and rate (m y^{-1})	(−4.9)	(+7.0)
Area change ($m^2 \times 10^3$) above MHWM (Fig. 12)	−86	+102
and rate ($m^2 \times 10^3$ y^{-1})	(−3.0)	(+3.5)

4. Both Smith (1976) and Gibb (1977) noted that the positions of the AD 131 and AD 1050 shorelines on Ohope spit are defined approximately by the areal distribution of the Taupo Pumice and Kaharoa Ash respectively. The Kaharoa Ash occurs seawards of the Taupo Pumice as well as some 3800 m further east, suggesting that the spit had grown this amount in the intervening 900 years between eruptions.

The above evidence suggests 2 possibilities for the late Holocene evolution of the Ohope-Ohiwa barrier spits. Either Ohope spit has grown eastwards across the Ohiwa embayment since eruption of the Taupo Pumice (AD 131) with the most rapid extension of c. 4 m y^{-1} occurring between that time and eruption of the Kaharoa Ash. The width of the harbour mouth and the size of Ohiwa spit at this time are not known. Alternatively, the "original" late Holocene entrance to Ohiwa Harbour may have occurred opposite the Wainui arm near the middle of the Ohiwa embayment, the entrance subsequently migrating under the pressure of eastward drift. As Davies (1977) demonstrates, opposing barrier spits can be caused simply by wave refraction through the entrance and need not imply opposing drift systems.

5. For the final stages of the harbour evolution, and coincident with the growth of Ohope spit, tidal channel migration and wave-lap have eroded parts of the harbour-side of the spit. Spit growth is presently asymmetrical with a seawards progradation adjoining the subtidal delta. Such cuspate forelands are general features of many northeastern New Zealand barriers (Healy & Kirk 1982), and are evidence of sediment surplus. Throughout its late Holocene development Ohiwa Harbour infilled to reach its present stage of 70% surface area exposed at low tide. Infilling is continuing, fed primarily from the littoral drift (Healy et al. 1977; Healy 1978). Gibb (1977) deduced an c. 36% reduction in tidal compartment over the past 100 years, which gives independent evidence of rapid harbour infilling.

CONCLUSIONS

1. Ohiwa Harbour is a tidally-dominated estuarine lagoon separated from the open ocean Bay of Plenty by the eastwards accreting, major (6 km long) Ohope barrier sand spit in the west, and the eastwards eroding, minor (0.7 km long) Ohiwa sand spit in the east. Seventy percent of the 24 km^2 harbour comprises tidal flats.
2. Sediments are typically rippled and megarippled, well sorted, medium to fine sands in lower harbour barrier beach, dune and entrance channel and shoal subenvironments; and bioturbated, poorly sorted, fine to very fine (silty) sands in the extensive upper harbour intertidal flats, banks, channels, and creeks. These sediment textural maturity contrasts reflect mainly the overall upharbour decrease in energy of tidal flows.
3. Biological communities, both plant and animal, play an important role in harbour sedimentation by reworking, stabilising, trapping, and supplying sediment, especially on the tidal flats.
4. The glass/pumice/plagioclase feldspar/quartz-dominated sediment mineralogy has been supplied mainly via the oceanic littoral zone from an ultimate acid volcanic provenance, with probably only minor contributions from the Ohiwa catchment itself.
5. Following the AD 131 Taupo Pumice eruption it is suggested that the formerly rapidly prograding Rangitaiki Plains in the Whakatane graben, up-drift

and west from Ohiwa, reached a critical stage of geomorphic development. Since this time much of the oversupply of volcanogenic sand supplied to the littoral zone by the major Tarawera, Rangitaiki, and Whakatane Rivers moved eastwards around Whakatane Heads infilling Ohiwa Harbour and accelerating formation of the Ohope-Ohiwa barrier sand spits.

6. Over the last 2000 years Ohope spit has accreted laterally eastwards at an average rate of about 3 m y^{-1}, Ohiwa spit has at the same time eroded, and there has been accelerated infilling of Ohiwa Harbour to reach its present stage of 70% surface area exposed at low tide.

7. Erosion of Ohiwa spit has been long term and is likely to continue in future. Given historical rates, the tidal inlet to Ohiwa Harbour could abut against bedrock on the eastern side of the harbour within 90–250 years, completely eliminating Ohiwa spit.

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